Geomorphological Classification of the Benthic Structures on a Tropical Continental Shelf

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Geomorphological research offers a valuable first step to understand the complexity of seafloor patterns that are likely to support particular fauna, thereby providing value for future targeted studies on benthic communities and habitats. The objective of this study is to perform a geomorphological classification of a tropical continental shelf, located in the north of the State of Pernambuco, Brazil, using Benthic Terrain Modeler (BTM), as a first step to characterize benthic habitats. The classification of the seabed is based on the bathymetry, broad-scale and fine-scale BPI (Benthic Positioning Index), seafloor slope, and a decision table containing definitions and thresholds appropriate to the data input. The relationships between morphology and the deposition of surface sediments were also investigated. Results from the BTM analysis revealed eight types of benthic structures: Flat Plains, Depressions, Gentle Slopes, Steep Slopes, Flat Ridge Tops, Rock Outcrop Highs, Local Pinnacles in Depressions and Local Pinnacles on Broad Flats. The results from this study may therefore assist in selecting priority areas to investigate, supporting better marine spatial planning in the region, and, in the future, collaborating to determine biodiversity patterns in Brazilian waters.

Keywords: potential habitats, Benthic Terrain Modeler, terrain attributes, single-beam echosounder, tropical Atlantic Ocean

INTRODUCTION

Geomorphological research is a tool to understand the complexity of seafloor patterns. These patterns can condition a number of environmental characteristics, such as light incidence, exposure to currents and waves, nutrient availability, substrate, erosion, or sediment deposition (Post, 2008; Verfaillie et al., 2009; Harris, 2012), providing a range of spatiotemporal influences on the habitat suitability of an area for benthic fauna and flora (Post et al., 2011; Lecours et al., 2015).

Within the context of seafloor habitat mapping, the term "habitat" has been defined and used in various ways (Brown et al., 2011). For example, Harris and Baker (2012) define benthic marine habitats as geographically distinct areas of the seafloor, where physical characteristics are associated with species or communities that occur consistently together. Similarly, other studies have utilized (geo) statistical methods to examine the relationship between physical, chemical and biological characteristics of the seafloor to spatially define habitats with similar characteristics (e.g., Brown et al., 2012; Lecours et al., 2016). Spatial scale in defining habitat is often a complicating factor (see discussion in Lecours et al., 2015), with several seafloors habitat mapping studies now adopting a landscape-scale approach analogous to mapping biophysical patterns in the terrestrial

environment. This broad-scale approach, often underpinned by acoustic seafloor mapping data validated with *in situ* ground validation, is often referred to as "seascape" (Pittman et al., 2007), or "benthoscape" mapping (Zajac et al., 2003; Zajac, 2008; Brown et al., 2012).

"Potential habitat," as proposed by Greene et al. (2005), describes a set of distinct physical seafloor conditions (e.g., landforms, texture, etc.) without incorporating any *in situ* geological/biological ground validation data. Specific associations between the seafloor biology and the physical attributes may not be known at the initial stage of defining and mapping the potential habitats of a study site, but may be investigated at some stage in the future to define "actual habitats" (Greene et al., 2007). Potential habitat mapping, accomplished through terrain attributes, offers a robust methodology to understand the spatial distribution and complexity of benthic habitats where ground validation data is scarce (Rinne et al., 2014). It is also a valuable means of highlighting species-environment relationships routinely integrated into environmental studies around the world (Lecours et al., 2016) which, until now, have been lacking for the South Atlantic Ocean (Harris and Baker, 2012). The benthic structures describe features of seafloor geomorphology, which can be determined using spatial statistical analysis available within various Geographic Information System (GIS) software packages.

In this study, the benthic structures and their distribution on a tropical continental shelf, located in the north of the State of Pernambuco – Brazil, were investigated through geomorphological classification. Furthermore, the relationships between morphology and the deposition of surface sediments were also investigated, aiming to present the first potential benthic habitats classification for this tropical area, particularly important for ecosystem studies, since the morphology affects the distribution of benthic communities.

The study area (91 km^2) is located on the continental shelf between the coastline and the 20 m isobaths, in the northern region of the Port of Recife (Pernambuco–Brazil) (**Figure 1**). In this area, the continental shelf is 34 km wide to a maximum depth of 60 m (Camargo et al., 2015). The characteristics of the Pernambuco continental shelf are a reflection of the low continental sedimentary contribution, of the predominant tropical climate (Goes and Ferreira, 2017) and tectonism (Vital et al., 2005). Its shallow depth is related to the inefficiency of the marine processes in recent geological periods (Manso et al., 2004).

One of the main features of the northeastern Brazilian coast and continental shelf is the peculiar characteristics of coral reef and beachrock features parallel to the main shoreline axis (Laborel, 1965; Dominguez et al., 1990; Maida and Ferreira, 1997; Costa et al., 2016; Leão et al., 2016). On the shallower portion of the Pernambuco continental shelf, the presence of beachrocks is a striking feature in the landscape. These sedimentary rocks are intertidal in the shallower parts running parallel to the shoreline, and are exposed during low tides, while remaining completely submerged at greater depths (Mabesoone, 1964; Laborel, 1970; Maida and Ferreira, 1997). The topography of the continental shelf includes both positive and negative features (reef banks of

various origins, channels, among others), and the micro relief is a direct response of the seafloor to the prevailing hydrodynamic conditions (Araújo et al., 2004; Costa et al., 2016).

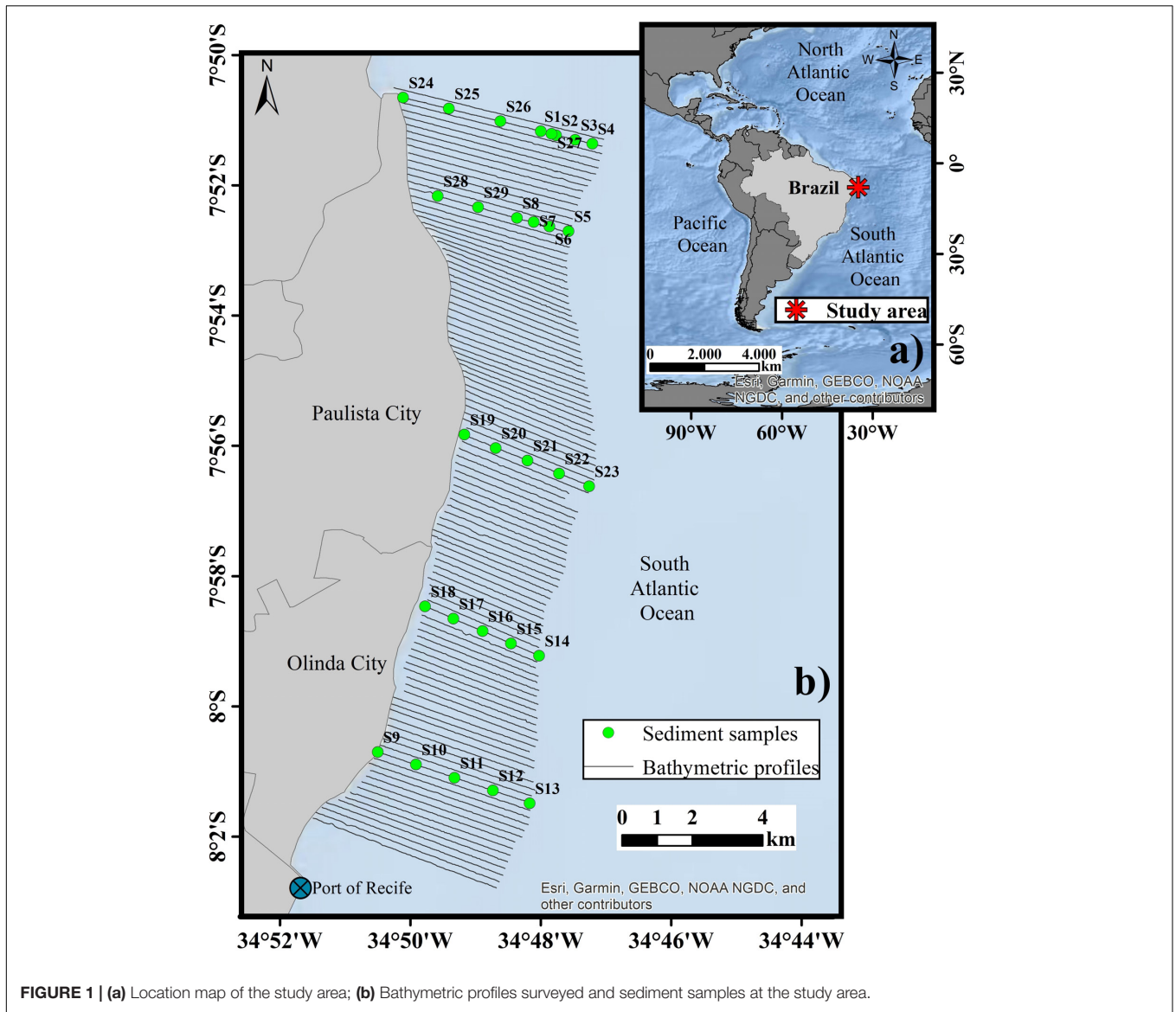## MATERIALS AND METHODS

Bathymetric Data

The bathymetric database consists of single-beam echosoundings, collected in the scope of MAI Project (Financiadora de Estudos e Projetos [FINEP] and Universidade Federal de Pernambuco [UFPE], 2009). It was performed using a single-beam echosounder, operating at 200 kHz and integrating a Garmin 298 GPS with antenna for navigation and positioning, at a sampling rate of three soundings per seconds. For this study, 110 profiles were conducted between the coastline and the 20 m isobaths (**Figure 1**). These profiles were arranged perpendicular to the main axis of the coast and were spaced at approximate intervals of 200 m. All depth values were adjusted for tidal variation using tidal prediction form the Brazilian Hydrographic Service.

All bathymetric data (55,102 points) were pooled and submitted to a natural neighbor interpolation method to create a raster surface with 10 m cell size, to generate a digital bathymetric model (DBM) of the seafloor. This cell size was chosen because it best represented the existing conditions in the bathymetric profiles. Other tests were performed, with cells of 20, 40, and 100 m, in which loss of resolution was observed when comparing the interpolated surface to the bathymetric profiles of the area.

Increased survey density and use of multibeam echosounders provide the opportunity for higher reliability hydrographic survey, which would improve identification of seafloor morphology. The existing data set, with widely spaced survey lines, generates anisotropic effects in the spatial interpolation, creating artifacts, which are present in the final digital elevation model of the seafloor. This is an inherent issue related to the available survey data set. It should be noted that in a study comparing the accuracy of single-beam echo-sounder (SBE) against multibeam echo-sounder (MBE), it was found that maps produced with data acquired with the first have an average of 84% accuracy, while the second 91% (Parnum et al., 2009). We therefore consider the accuracy of the data for this study fit for purpose, allowing the first broad-scale.

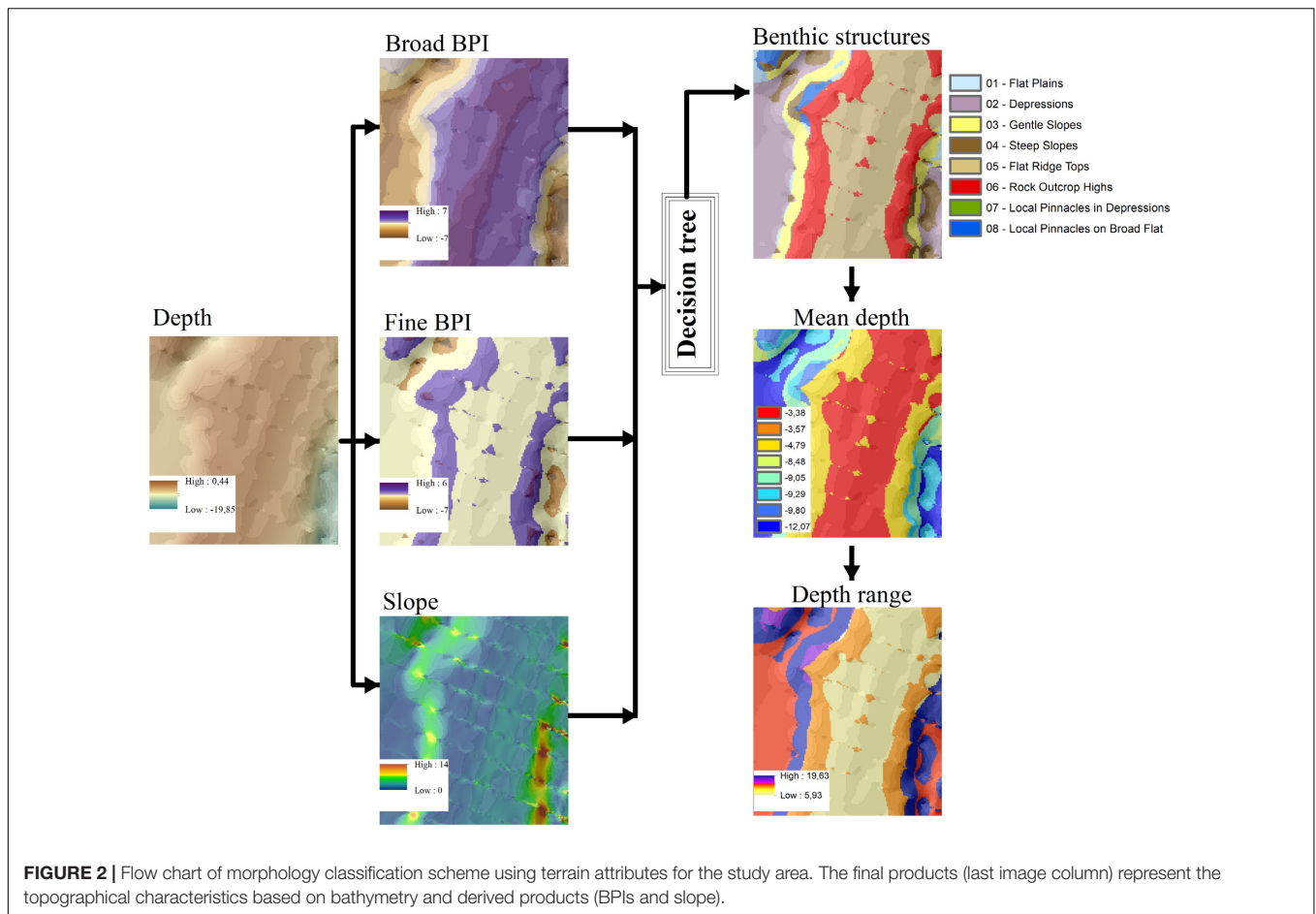### Terrain Attributes Derived From Bathymetric Data

Terrain attributes can be quantitatively measured in a three-dimensional space and related to wildlife dynamics, making for the well-established field of geomorphometry (Bouchet et al., 2015). Then, these attributes derived from bathymetric data can be used as proxies for habitat studies (Bargain et al., 2018). As shown in the Digital Bathymetric Model (DBM) (**Figure 2**), terrain attributes such as seafloor slope and Bathymetric Position Index (BPI - at fine and broad-scales) were derived using the Benthic Terrain Modeler (BTM), an extension to ArcGIS (versions 10.x).

FIGURE 1 | (a) Location map of the study area; **(b)** Bathymetric profiles surveyed and sediment samples at the study area.

Benthic Terrain Modeler is a GIS classification approach, which uses a combination of derived terrain attributes to segment the seafloor into geomorphic classes. It was developed by the Department of Geosciences of Oregon State University in collaboration with the National Oceanic and Atmospheric Administration (NOAA) GIS Integration and Development Program (Wright et al., 2005; Lundblad et al., 2006). Slope is defined as a gradient toward the maximum slope of the ocean floor (Lundblad et al., 2006; Jerosch et al., 2015). Expressed in degrees, it is understood as a fundamental ground attribute to the analysis of the seafloor, whereas the slope of the terrain exerts influence on the currents, influencing the rate of erosion in a given area and allowing different adjustments to the distribution of organisms (Kostylev et al., 2003). BPI is a measure of relative elevation of the general marine landscape. It calculates, on user-defined scales, the difference between the elevation of a DBM focal cell relative to the average elevation of surrounding cells

(Erdey-Heydorn, 2008; Jerosch et al., 2015). Negative BPI values mean that focal cells have lower values than the surrounding cells, configuring structures such as valleys. Positive BPI values mean that focal cells have higher values than their surrounding ones, forming structures such as ridges. BPI values close to zero are related to flat or constant slope areas (Lundblad et al., 2006).

Once BPI data sets were created at both fine and broad-scales, the next step in the classification process was to standardize the values of these raster data sets, because the elevation tends to be spatially auto-correlated (Weiss, 2001; Erdey-Heydorn, 2008). These BPI data were standardized by subtracting the mean value of the BPI data from each BPI data point and dividing by the standard deviation; in this way the BPI data point had a value of 0 and the standard deviation had a value of $-1/1$. The standardized value of each data point was then multiplied by 100 (Wienberg et al., 2013). This allows for the same basic equations to be used to classify any scale combinations of BPI grids. The

FIGURE 2 | Flow chart of morphology classification scheme using terrain attributes for the study area. The final products (last image column) represent the topographical characteristics based on bathymetry and derived products (BPIs and slope).

exact breakpoints among classes can be manually chosen to optimize the classification for a particular landscape and problem (Weiss, 2001). Therefore, conclusions about the structure of the overall seascape were produced with spatial analysis by applying an algorithm that combines standardized BPI grids of different scales with slope and bathymetry (Lundblad et al., 2006).

Geomorphological Classification

The geomorphological classification is based on the ensemble analysis between DBM, broad-scale and fine-scale of the Bathymetric Position Index (BPI), and slope (**Figure 2**). A decision table containing definitions and thresholds is applied to the data to classify the existing benthic structures in the study area (**Table 1**). The decision table used in this work is based on and adapted from previous works (Lundblad et al., 2006; Erdey-Heydorn, 2008; Wienberg et al., 2013), and defines eight benthic structure/potential habitats. These are Flat Plains (ID 01), Depressions (ID 02), Gentle Slopes (ID 03), Steep Slopes (ID 04), Flat Ridge Tops (ID 05), Rock Outcrop Highs (ID 06), Local Pinnacles in Depressions (ID 07), and Local Pinnacles on Broad Flats (ID 08).

In order to obtain BPI in broad and fine-scales, inputs such as those from the literature (Lundblad et al., 2006; Erdey-Heydorn, 2008; Wienberg et al., 2013), were adapted to meet the

requirements of the morphology of this tropical continental shelf. For fine-scale BPI, an internal radius of 10m and an external radius of 25 m were used. For the broad-scale, an internal radius of 10 m and an external radius of 100 m were chosen.

In the BTM, slope and the BPI grids were computed from the bathymetry raster. To avoid the influence of spatial autocorrelation in the broad-scale and fine-scale BPIs, the BPIs were standardized to 1 standard deviation, as proposed by Weiss (2001). For the geomorphological classification of the seafloor, the slope was used in the decision table (**Table 1**) to distinguish the thresholds between Flat Plains (ID 01) (up to 1 degree inclination), Gentle Slopes (ID 03) (1 to 5 degrees inclination), Steep slopes (greater than 5 degrees inclination) and Local Pinnacles on Broad Flats (ID 08) (up to 1 degree inclination). Previous studies conducted in areas with a large variation in depth have also used bathymetry (depth values) in the decision table to define benthic structures (Erdey-Heydorn, 2008). As the seafloor in our study site is delimited to 20 m isobath, the seafloor classes were not differentiated based on depth.

Sedimentological Characterization of Seafloor Classes

The relationships between morphology and the deposition of surface sediments were also investigated. The benthic structures,

TABLE 1 | Decision table summarizing the factors used for the definition of benthic structures in the study area.

ID	Benthic structures	Broad-scale BPI		Fine scale BPI		Slope	
		Lower	Upper	Lower	Upper	Lower	Upper
01	Flat Plains	−100	100	−100	100		1
02	Depressions	−100	100		−100		
03	Gentle Slopes	−100	100	−100	100	1	5
04	Steep Slopes	−100	100	−100	100	5	
05	Flat Ridge Tops	100		−100	100		
06	Rock Outcrop Highs	100		100			
07	Local Pinnacles in Depressions	100			−100		
08	Local Pinnacles on Broad Flats	−100	100	100			1

derived from the BTM analysis, were also analyzed in conjunction with the spatial variability of (gravel, sand and mud) fractions of the surface sediment samples.

Sedimentological characteristics were derived from 29 surficial grab samples (locations on **Figure 1**). The sedimentological analysis followed the methodology proposed by Suguio (1973) with wet and dry sieving. The resulting, sediment grain size (McLane, 1995) were analyzed using SysGran software and classified according to Folk (1954) into three classes: Gravel (>2 mm); Sand (2–0.062 mm); and Mud (<0.062 mm). In order to correlate the seafloor classes/benthic structures with the sedimentary surface composition, the percentages of mud (silt + clay), sand and gravel content of all the samples were also calculated.

RESULTS

Benthic Structures

Based on the grids of bathymetry, slope, BPIs broad-scale and fine-scale, and the decision table (**Table 1**), eight classes of benthic structures were differentiated by the BTM (**Figure 3**). In relation to bathymetry, the DBM (**Figure 3**) revealed the identification of the heterogeneity of the geomorphological features, both in size and location, mainly due to the occurrence of bank reefs and channels. In the northern part of the study area, the bank reef is closed (i.e., attached) to the coast. However, in the central part it is possible to identify the presence of two elongated bank reefs, not attached to the coast, with channels between them.

In the transition to the southern part of the area, the presence of the reef banks is not as distinctive, occurring only as discontinuous features (small patches). The bank reefs are once again present in the southern region of the study site, but not as distinguished as in the central part of the area. The most pronounced changes in the slope are related to the heterogeneity of the depth gradient, delineating the occurrence of the positive and negative reliefs.

Broad-scale BPI demonstrates the major features of the marine landscape (e.g., reefs and channels), while the fine-scale BPI captures the subtler differences in the study area (e.g., outer edges of reefs). According to the broad-scale BPI, the reef and channel demarcation is observed where the mathematically higher differences (7) coincide with the reefs, while the lower (−7) coincide with the channels. The Fine-scale BPI highlight the subtle differences in the study area. This BPI grid shows the surrounding sectors of the large features (e.g. reefs and channels), marking the boundaries between these features and the flat regions of the seafloor.

Finally, eight classes of benthic structures (**Figure 3** and **Table 2**) were recognized, occupying different percentages of surface on the explored area: Flat Plains (49.22%), Depressions (16.10%), Gentle Slopes (8.56%), Steep Slopes (5.03%), Flat Ridge Tops (5.80%), Rock Outcrop Highs (9.98%), Local Pinnacles in Depressions (>1%), and Local Pinnacles on Broad Flats (5.28%).

The Flat Plain (ID 01), was the most predominant class in the study area (49.22%), and was defined as the flat regions of the seafloor with BPI values close to zero. They are within the standard deviation of the mean (0) and have a soft slope (up to 1 degree inclination). Moreover, these areas have few changes in fine-scale BPI. Depressions (ID 02) were defined as low points on the ground, with BPIs values greater than one standard deviation from the mean in the negative direction (−1), occurring in 16.10% of the area.

Gentle Slopes (ID 03) were simpler relief zones, with no alternating of concave and convex areas. They have BPI close to zero, within the standard deviation of the mean (0), with slope varying between 1 and 5 degrees. In contrast, Steep Slopes (ID 04) were extensive regions of sloping seafloor, of BPI close to zero, within the standard deviation of the mean (0), with slope values greater than 5 degrees.

Flat Ridge Tops (ID 05) were areas where flat, broad-scale seafloor features are higher than the surrounding seafloor, and primarily comprising the top of narrow, linear structures running parallel to the coastline and without any slope. Rock Outcrop Highs (ID 06) were bathymetric high points in the field, with positive BPI values greater than one standard deviation of the mean in the positive direction (1). In these zones, the fine-scale and broad-scale features were less deep than the surroundings.

The Local Pinnacles in Depressions (ID 07) were narrow ridges within a sunken terrain, represented by the fine-scale BPI. They can be considered as high points in the field with positive BPI values greater than one standard deviation of the mean in the positive direction (1). Similarly, Local Pinnacles on Broad Flats (ID 08), correspond to narrow crests within a broader flat region of the seafloor highlighted by the fine-scale BPI. Like Local Pinnacles in Depressions (ID 07), they are considered as high points on the ground with positive BPI values greater than one standard deviation of the mean in the positive direction (1).

Association of Benthic Structures and Grain Size of the Surface Sediment

The analysis of the samples collected along the area also revealed the variety of sediment composition (**Figure 4** and **Table 3**), according to the final classification shown in
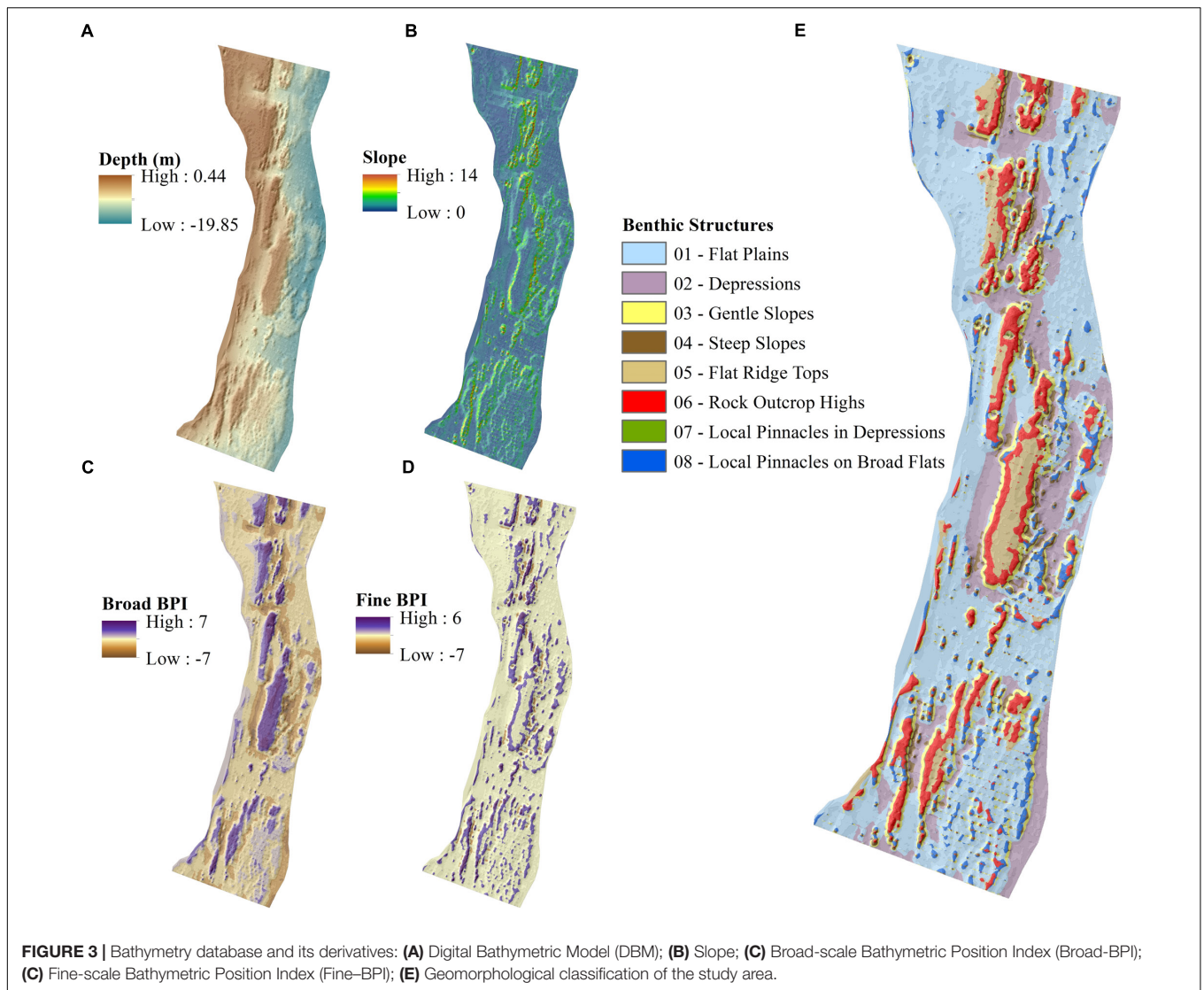
FIGURE 3 | Bathymetry database and its derivatives: (A) Digital Bathymetric Model (DBM); (B) Slope; (C) Broad-scale Bathymetric Position Index (Broad-BPI); (C) Fine-scale Bathymetric Position Index (Fine–BPI); (E) Geomorphological classification of the study area.

TABLE 2 | Depth-related description of the geomorphological classification and the percentage of occurrence.

Structures				Depth				
ID		Area (km²)	Area (%)	Min. (m)	Max. (m)	Mean (m)	Range	STD
01	Flat Plains	44.78	49.22	−19.31	0.33	−8.48	19.64	5.63
02	Depressions	14.65	16.10	−19.86	−2.64	−12.07	17.21	4.29
03	Gentle Slopes	7.79	8.56	−19.26	0.23	−9.06	19.48	4.13
04	Steep Slopes	4.58	5.03	−19.28	0.32	−9.30	19.60	3.91
05	Flat Ridge Tops	5.28	5.80	−14.88	0.29	−3.39	15.17	2.87
06	Rock Outcrop Highs	9.08	9.98	−16.34	0.43	−4.79	16.78	3.69
07	Local Pinnacles in Depressions	0.01	0.01	−8.74	−2.80	−3.57	5.94	1.05
08	Local Pinnacles on Broad Flat	4.81	5.29	−18.23	0.44	−9.81	18.67	4.66

Figure 3E. In relation to the sedimentological composition (gravel, sand, and mud), it is observed that in the Depressions (ID 02) there is a predominance of sand, while in the Gentle Slopes (ID 03) there is an alternation between the dominance of the percentages of gravel and sand.

In Local Pinnacles on Broad Flats, there is a predominance of gravel, and in the Flat Plains (ID 01), there is a substantial variation among the percentages of the sediment components; however, it is in this structure that the highest percentages of mud are found. Flat Ridge Tops (ID 05) are represented by a
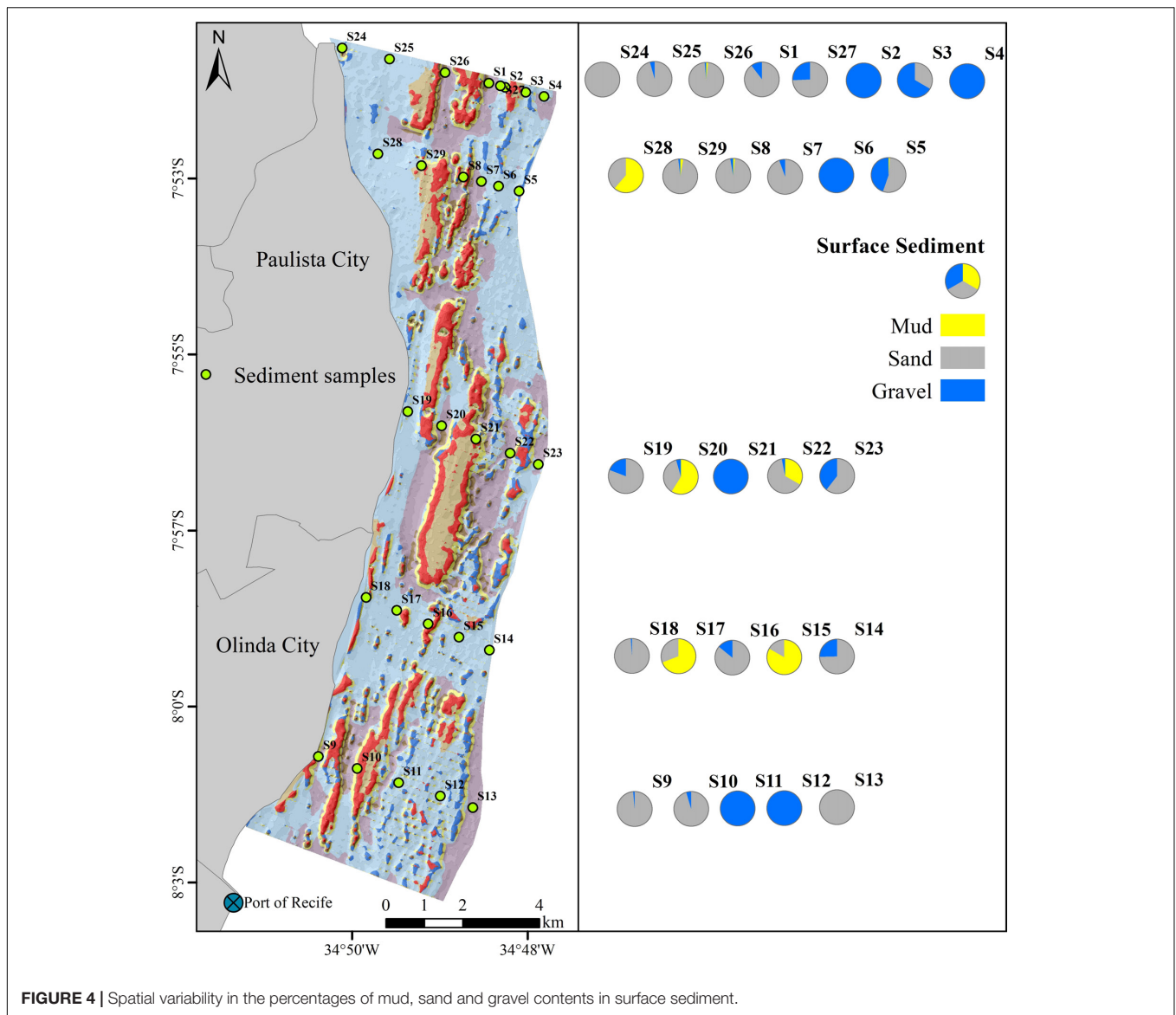
FIGURE 4 | Spatial variability in the percentages of mud, sand and gravel contents in surface sediment.

higher percentage of sand while in Rock Outcrop Highs (ID 06) an alternation of larger values between gravel and sand was observed.
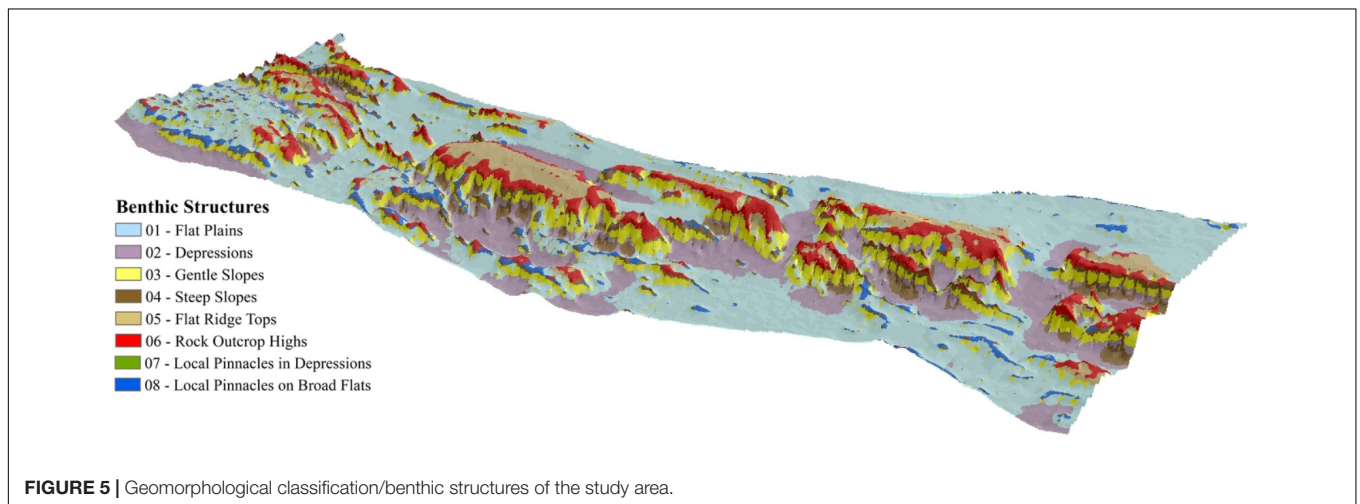
DISCUSSION

In the study area, eight geomorphological classes are defined by the BTM, recognized as benthic structures (**Figure 5**). The benthic structures that occur in this tropical area highlight the heterogeneity and diversity of the seafloor of the study area. The results of the methodological process used in this study provide an unprecedented recognition of the relief patterns for the study area, not described in any previous study. The final classification can be considered a "potential habitat map" (Greene et al., 2007) and adds to the knowledge and understanding of the environmental characteristics of this area, but does not provide

a complete description of benthic habitats for the study area due to the limited amount of ground validation data. However, particularly for ecosystem studies, can be considered that the morphology affects the distribution of benthic communities, influencing environmental factors (e.g. substrate, erosion or sediment deposition, currents and available nutrients) (Lundblad et al., 2006; Jerosch et al., 2015). On the other hand, according to Dartnell and Gardner (2004), a basic data set that describes the surficial characteristics of the seafloor is the baseline used for a habitat study, therefore important for ecological studies.

Although multibeam echosounder have emerged as the tool of choice for seafloor habitat modeling, because of their ability to collect both bathymetry and backscatter information simultaneously (Mumm, 2015), the use of single beam echosounder also demonstrates reasonable accuracy in seafloor habitat mapping (Parnum et al., 2009). In this sense, the proposed methodology, through the use of the BTM extension,

TABLE 3 | Mean grain size, percentages of gravel, sand, and mud of surface sediment.

ID	Benthic structures	Samples	Mean (mm)	% Gravel	% Sand	%Mud	Textural classification
01	Flat Plains	S2	–	100.00	0.00	0.00	Gravel
01	Flat Plains	S3	1.9924	66.60	33.30	0.10	Sand
01	Flat Plains	S11	–	100.00	0.00	0.00	Gravel
01	Flat Plains	S14	0.8536	25.17	74.64	0.18	Sand
01	Flat Plains	S15	0.0198	0.14	16.85	83.02	Mud
01	Flat Plains	S17	0.0410	0.28	30.80	68.92	Mud
01	Flat Plains	S18	0.4222	1.05	98.20	0.75	Sand
01	Flat Plains	S19	1.1237	19.08	80.67	0.25	Sand
01	Flat Plains	S25	0.6018	4.36	94.94	0.70	Sand
01	Flat Plains	S27	1.1340	25.69	74.11	0.20	Sand
01	Flat Plains	S28	0.0243	0.1256	38.64	61.24	Mud
02	Depressions	S7	0.9991	5.586	94.24	0.17	Sand
02	Depressions	S13	0.5719	0.27	99.47	0.27	Sand
02	Depressions	S20	0.0561	4.386	36.69	58.93	Mud
02	Depressions	S22	0.1436	3.15	63.64	33.21	Sand
02	Depressions	S23	1.4803	39.45	60.41	0.14	Sand
03	Gentle Slopes	S1	1.0529	10.32	89.51	0.17	Sand
03	Gentle Slopes	S8	0.6851	2.931	95.32	1.74	Sand
03	Gentle Slopes	S10	0.9095	4.66	95.27	0.07	Sand
03	Gentle Slopes	S12	–	100.00	0.00	0.00	Gravel
03	Gentle Slopes	S24	0.2050	0	99.66	0.34	Sand
03	Gentle Slopes	S26	0.4494	1.397	97	1.61	Sand
05	Flat Ridge Tops	S29	0.2270	1.939	95.29	2.77	Sand
06	Rock Outcrop Highs	S9	0.3025	1.417	97.84	0.74	Sand
06	Rock Outcrop Highs	S16	1.0254	14.01	85.79	0.20	Sand
06	Rock Outcrop Highs	S21	–	100.00	0.00	0.00	Gravel
08	Local Pinnacles on Broad Flats	S4	–	100.00	0.00	0.00	Gravel
08	Local Pinnacles on Broad Flats	S5	1.1252	44.82	54.11	1.07	Sand
08	Local Pinnacles on Broad Flats	S6	–	100.00	0.00	0.00	Gravel

Benthic Structures
- 01 - Flat Plains
- 02 - Depressions
- 03 - Gentle Slopes
- 04 - Steep Slopes
- 05 - Flat Ridge Tops
- 06 - Rock Outcrop Highs
- 07 - Local Pinnacles in Depressions
- 08 - Local Pinnacles on Broad Flats

FIGURE 5 | Geomorphological classification/benthic structures of the study area.

functions as a first step for mapping the ocean floor, especially considering the widely spaced nature of available single beam surveys and the scarcity of multibeam survey data for this area. Wide spacing of survey lines creates anisotropic features in the spatial interpolation and may therefore influence the benthic habitat classification. However, in this location, the anisotropy is considered to be strongly offset by the geological structure, with long rocky ridges running almost parallel to shore. Residual effects of the interpolation include limited ability to identify slopes except along the survey lines, and large horizontal uncertainty in the alongshore scale and position of discontinuities, such as gaps between rock ridges. The constraints

of survey coverage should be considered in conjunction with known characteristics of the local morphology when applying BTM to develop a potential benthic habitat model.

Pereira and Bonetti Filho (2018) presented an analysis of the background relief of three Brazilian conservation units, also from the BTM extension. National Marine Park of Fernando de Noronha (PARNAMAR Noronha), National Marine Park of Abrolhos (PARNAMAR Abrolhos), and the Biological Marine Reserve of Arvoredo (REBIOMAR Arvoredo). The analysis concluded that these areas have great morphological complexity of the seafloor. They suggested that the high biodiversity indexes, to a certain degree, may be associated with the high seafloor morphological complexity of the respective benthic structures (Pereira and Bonetti Filho, 2018).

Analysis of the sediment grain size samples in our study indicated that the highest percentage of mud was found in the Flat Plains (ID 01), while the Rock Outcrop Highs (ID 06) are marked by high levels of gravel. Likewise, in the northern region of the area, samples collected on structures classified as Local Pinnacles on Broad Flats (ID 08) were characterized by high gravel content. This configuration is observed in analyses conducted in the Weddell Sea, where coarser grain sizes appear in more exposed geomorphic features, such as crests and outcrops (Jerosch et al., 2015).

Such variation of the surficial sediment characteristics may indicate that this area has a greater variation in the communities that are associated to the sector, whereas different organisms suit the area depending on their particularities (Post, 2008; Verfaillie et al., 2009; McArthur et al., 2010). These patterns indicate possible heterogeneity in the potential distribution of benthic habitats, since changes in depth and mud contents are strongly correlated, and reflect distinct processes of association of benthic communities (Post et al., 2011).

Prominent structures on the seafloor in the study area may serve as useful proxies for estimating areas of higher biodiversity (Bouchet et al., 2015). Furthermore, the complexity of the rock forms itself presents both a greater surficial area for colonization and a greater variety of niche habitats than would a flat rock surface (Diesing et al., 2009).

The peculiar characteristics of coral reef and beachrocks feature parallel to the main shoreline axis (Laborel, 1965; Dominguez et al., 1990; Maida and Ferreira, 1997; Costa et al., 2016; Leão et al., 2016) is remarkable in this study area. These features are represented by the alternation of positive and negative BPIs, in addition to a relatively large slope.

It is concluded that approximately 40% of the area is formed by Gentle Slopes (ID 03), Steep Slopes (ID 04), Rock Outcrop Highs (ID 06), and Depressions (ID 02). These areas, which present greater morphological complexity, probably indicate regions supporting high biodiversity, given that geometrically complex surfaces are known to provide an abundance of stable, niche habitats exploited by a wide diversity of species (Kostylev et al., 2003; McArthur et al., 2010; Zawada et al., 2010; Darling et al., 2017). For this reason, they constitute a key ecological factor often positively linked to biodiversity and carry capacity of habitats (Yanovski

et al., 2017; Rees et al., 2018). In contrast, 49.22% of the area is formed by Flat Plains (ID 01). These areas with low morphological complexity can be considered areas of lower biodiversity, as already observed in other studies (e.g., Kostylev et al., 2003; McArthur et al., 2010; Zawada et al., 2010; Darling et al., 2017).

The habitat heterogeneity, offered by this seafloor complexity, such as beachrocks features, is often associated with high biodiversity (Gladstone, 2007; Guevara-Fletcher et al., 2011). Studies have shown that features on the Australian shelf provide three-dimensional structures supporting benthic communities that contrast with the adjacent seabed, which is often flat (Brooke et al., 2017). Therefore, the importance of the recognition of the structural patterns present in the study area for marine environmental conservation and management plans is emphasized (Riegl and Piller, 2003).

Recently, Rinne et al. (2014) used large-scale bathymetric data to designate geographically complex areas of reef occurrences through the geomorphological analysis of the benthoscape on the northern Baltic Sea, with subsequent validation of the prediction ground-truthing. The results from our study may therefore assist in selecting priority areas to investigate, supporting improved marine spatial planning in the region, and, in the future, collaborate to determine biodiversity patterns. Furthermore, the results obtained in this work contribute to the achievement of the Aich Targets 2011–2020, regarding the improvement of the knowledge, scientific base and technologies related to the biodiversity in the Brazilian continental waters, besides the diffusion of generated knowledge (Ministério do Meio Ambiente [MMA], 2017).

Finally, this study has generated the first model of potential benthic habitats for this tropical area, which is particularly important for ecosystem studies. Over wider spatial scales or with coarser data resolutions (such as GEBCO data for example), the geomorphic classification algorithm needs to be adjusted for the scale and resolution of the underlying data.

AUTHOR CONTRIBUTIONS

EG analyzed the data and prepared the manuscript. CB assisted in the preparation of the manuscript. TA secured funds, participated in field work, and assisted in the preparation of the manuscript. All authors have read and contributed to the final version of the text.

FUNDING

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