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Geomorphological complexity and its association with submerged aquatic vegetation on the Yucatán coast

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Abstract. Shallow marine ecosystems with extensive communities of submerged aquatic vegetation, including seagrasses and macroalgae, are found along the northern coast of the Yucatán Peninsula. This study describes the geomorphological complexity of the nearshore seafloor in Yucatán, Mexico, and its association with submerged aquatic vegetation communities, constituting the first effort of its kind in this region. This work is relevant because ecological interactions between the seafloor and its inhabitants define the spatial structure of ecosystems, as well as ecological processes, many of which provide benefits to human society. The objectives of this study were to: (1) spatially delineate discrete geomorphological units (structures and zones) based on their depth, slope, and aspect; (2) describe the relative abundance of major groups of submerged aquatic vegetation (seagrasses, green algae, red algae, brown algae, and algal turf); and (3) assess the association between geomorphology and the presence of the vegetation groups under study. This information establishes a baseline for biological, ecological, and oceanographic analyses of the coastal marine ecosystems in southeastern Mexico. In addition, the results of this study are crucial for decision-making related to coastal development, adaptive management, and environmental conservation monitoring, and provide a foundation for functional ecosystem assessment studies.

Key words: digital elevation model, bathymetric position index, Bayesian multinomial logistic models, base line, historic data.

Introduction

Ecological interactions shape the distribution of marine communities, which in turn influences the ecosystem functions they perform, including the provision of ecosystem services to human communities (hurricane protection, carbon sequestration, provision of attractive landscapes, and support of fishing activities), and the resilience of marine landscapes. Therefore, it is strategic to understand associations between the physical and biological characteristics of these landscapes (Gladstone-Gallagher et al. 2019, Armoskaite et al. 2020, Borland et al. 2021, Lavialle et al. 2023).

In particular, the geomorphology (Öhman and Rajasuriya 1998), relief, and substrate type (Khalaf and Kochzius 2002) are recognized as determining influences for the distribution of benthic communities of corals (Mayorga-Martínez et al.

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2021), macroinvertebrates in the intertidal zone (Damveld et al. 2018), and seagrasses and macroalgae (Hemminga and Duarte 2000), to the extent that some authors propose the evaluation of the topography and complexity of the seafloor as a substitute indicator of benthic biodiversity for a rapid sampling strategy (Cooper et al. 2019; Schenone et al. 2023, 2025). In this context, it is relevant to emphasize the relevance of evaluating the relationship between benthic communities and the seafloor at multiple scales, including both the individual components of complexity and the geomorphological classes themselves (Gratwicke and Speight 2005, Pygas et al. 2020).

The shallow marine ecosystems of the northern Yucatán Peninsula, southeastern Mexico, are characterized by the presence of consolidated and unconsolidated calcareous sediments, where submerged aquatic vegetation (SAV) communities, such as seagrasses and macroalgae, develop. These communities provide key benefits, both tangible and intangible, associated with the blue carbon cycle (Cota-Lucero and Herrera-Silveira 2021), facilitate the establishment of coastal sediments (Short et al. 2006), contribute to the stabilization of sediments associated with nearby sandy beaches (Christianen et al. 2013, James et al. 2019), and constitute critical habitats for fauna species of high commercial and ecological interest (Boström et al. 2006, Sandoval-Gío et al. 2020, Chen et al. 2021). In addition, these communities serve as the basis for important livelihood activities for various coastal communities in Yucatán (Rebours et al. 2014, Coronado et al. 2020, Arcos-Aguilar et al. 2021, Quiñones-Peraza et al. 2023).

Seagrass and macroalgal communities have been described in this region, but not for the entire northern coast of the peninsula; in addition, the geomorphological complexity of the seafloor has not been evaluated, nor has the association between these ecosystem components been assessed (Bello-Pineda and Hernández-Stefanoni 2007, Cota-Lucero and Herrera-Silveira 2021, Lópes de Olmos Reyes et al. 2023, Ortegón-Aznar et al. 2024). Thus, the present study has a pertinent and relevant impact by providing spatially explicit products that contribute to the management of this maritime territory, as well as historical data that are made public and constitute a baseline for assessing landscape changes. Furthermore, it joins the philosophy of open ocean data promoted by the Ocean Decade, among others (Martin et al. 2025).

In this context, this study presents a geomorphological characterization of the shallow nearshore seafloor of Yucatán, Mexico, at a landscape scale (tens of kilometers) and from the perspective of the physical variables of the seafloor. The objectives of this study were: (1) to spatially delimit discrete geomorphological units (structures and zones) based on their components of depth, slope, and aspect; (2) to describe the relative abundances of major groups of SAV (seagrasses, green algae, red algae, brown algae, and algal turf); and (3) to evaluate the association between geomorphology and the presence of SAV groups in the same period as the geomorphological classification.

Materials and methods

Study area

Yucatán is located in southeastern Mexico, north of the Yucatán Peninsula, which is of karst origin and has a submarine continental shelf of sedimentary rocks on a Paleozoic crystalline basement (Lugo-Hubp et al. 1992).

The region lacks surface rivers, but underground laminar flows are recognized through the karst structures (Solleiro-Rebolledo et al. 2011). Its coast is a plain characterized by a narrow strip of recent marine deposits of biogenic carbonate origin and an accumulation shoreline (Lugo-Hubp et al. 1992). The marine area has low-energy waves, with dominant surface currents and a potential sediment transport from east to west, as a result of the waves (Martínez-López and Parés-Sierra 1998, Enríquez et al. 2010, Appendini et al. 2012). Regarding its geomorphology, bathymetric survey information is available only for specific areas and from nautical charts (SEMAR 2019).

The region is home to diverse and productive ecosystems (coral reefs, soft coral colonies, rocky reefs, seagrass meadows, and macroalgal forests) of ecological (e.g., refuge and feeding sites for a wide variety of benthic and pelagic species) and commercial interest for the region (Zarco-Perelló et al. 2013, Palafox-Juárez and Liceaga-Correa 2017, Cota-Lucero and Herrera-Silveira 2021).

The study area comprised a 356-km long polygon delimited by the –12 m isobath in the open sea, which gave it a variable width. Our study area covered a total of 4,968 km^2 (Fig. 1). The methodological approach was conducted at a regional landscape scale (Gladstone-Gallagher et al. 2019, Schenone et al. 2023), based on techniques from geomatics and ecological disciplines to link physical data, derived from echo sounders, with biological data at the level of communities and large taxonomic groups; this addresses the current challenge in marine sciences of associating data at different scales, ensuring an efficient relationship between spatial resolution, coverage, and costs (Lark et al. 2015, Cooper et al. 2019, Brunier et al. 2020, Hao et al. 2023).

Bathymetric data collection

To collect bathymetric data, we used acoustic equipment. With the data, we generated a digital elevation model (DEM), which was used to spatially delineate discrete geomorphological units. For this, 170 equidistant transects (2 km apart) were defined, from north to south, perpendicular to the coastline, covering depths between the –0.5 m and –12.0 m isobaths (Fig. 1). These data were acquired from a small vessel (27 ft in length) with an outboard motor, at an average speed of 12 $km \cdot h^{-1}$, during the period from April 2012 to June 2013. The depth was measured with a Lowrance (Tulsa, USA) single-beam echosounder model LMS-37C (frequency: 200 MHz; beamwidth: 35°) coupled with an Ashteck (Gates

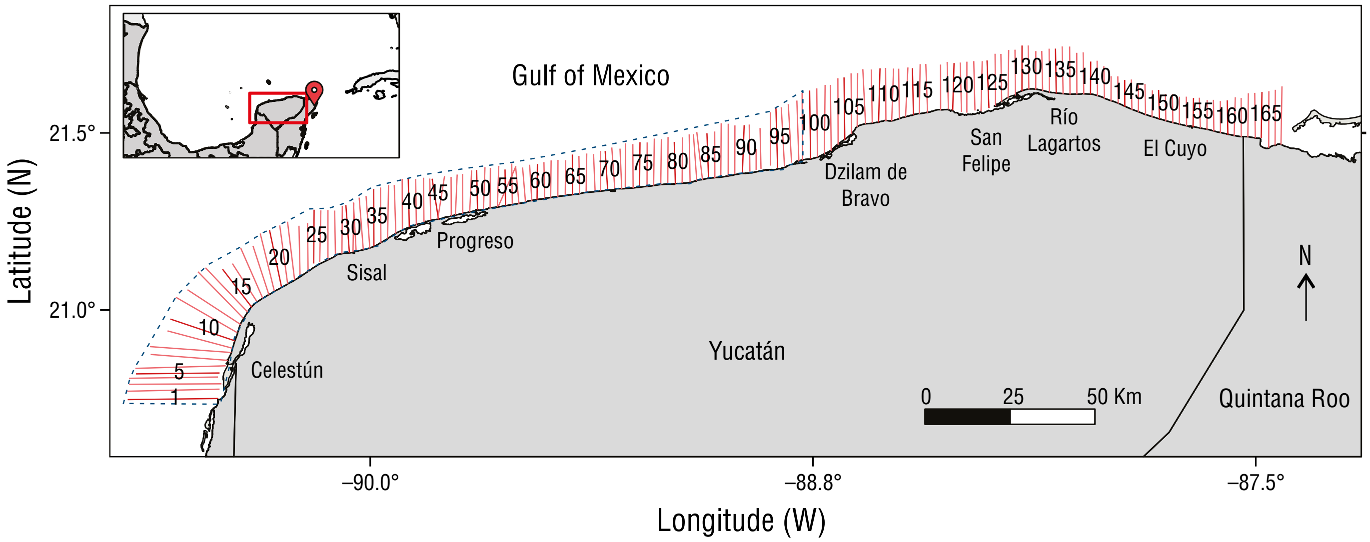

Figure 1. Study area on the northern shallow coast of the Yucatán Peninsula. The 170 transects (red lines perpendicular to the coast) used to collect bathymetric data are shown. The gray dotted line delimits the area for vegetation cover analysis. The main reference ports are indicated along the coast. In the macrolocation box, the red marker indicates the city of Cancún, as a reference location.

Mills, USA) differential global positioning system model Promark 500. The geographic coordinate data were orthometrically corrected in post-processing and, together with this article, the filtered data are made publicly available (https://goo.su/1RvqsCE). The boundary representing the coastline for the bathymetric model was defined by digitizing it in Landsat satellite images from the ETM+ sensor (spatial resolution: 30 m) obtained in April 2010 (Path/Row scenes: 19/045, 20/045, and 21/045).

Geomorphological classification of the seafloor

The distance between depth records on each transect was significantly smaller than the distance between 2 adjacent transects, which caused bias in the geostatistical model. To address this imbalance, a subset of bathymetric records (1,618 records) was selected from the centroids of a 2 × 2 km grid in the study area, thus standardizing the spatial resolution in both directions.

This data subset was assessed for spatial autocorrelation (semivariance) using the program Geostatistics for the Environmental Sciences (GS+) v. 9.0. We used the best-fitting nugget, range, and plateau parameterizations of the theoretical model in the semivariogram to construct a DEM by ordinary Kriging interpolation in ArcMap v. 10.2.2. Model accuracy was assessed by cross-validation analysis (predicted versus measured depth values) and by prediction efficiency (Villatoro et al. 2008), using a subset of the original bathymetric records (195,226 records; 20% of the total original data).

From the DEM, 2 of the main components of seafloor geomorphological complexity were calculated for multiscale categorization: slope and aspect (Wilson et al. 2007). These 2 components of marine relief, together with depth, play a preponderant role in configuring the geomorphological structures of the seafloor (Jerosch et al. 2015, Pygas et al. 2020). In this study, slope was defined as the maximum change in seafloor elevation within a given neighborhood, which is relevant to the sediment stability required for SAV to establish. Likewise, the orientation or aspect has a direct influence on the position of benthic communities with respect to the flow of currents and transportation of nutrients and was considered as the direction of the maximum inclination within the same neighborhood (Jerosch et al. 2015, Pygas et al. 2020). Both variables were generated in raster format using the Topographic Properties tool of the TNTmips program (Microimages, Raymond, USA) using the DEM.

For the geomorphological classification of the seafloor, the Benthic Terrain Modeler (BTM) v. 3.0 (ArcGIS v. 10.2.2) program was used with the bathymetric position index (BPI), which analyzes the values of each DEM pixel with respect to a set of pixels in a user-defined radial search neighborhood. Subsequently, based on a multivariate codification of the evaluated components (depth, slope, and aspect) and the BPI, the BTM program assigned a geomorphological classification to each DEM pixel (Wilson et al. 2007, Jerosch et al. 2015, Pygas et al. 2020).

In its calculation, the model included the analysis of the BPI index at 2 geographic scales for the radial search range. In this study, the fine (r) and broad (R) scale values were defined empirically and based on bibliographic references (Lundblad et al. 2006) with scales of 1:80,000 and 1:160,000. These values represented radial neighborhoods of 50 and 100 pixels for each pixel of the DEM, and both were standardized using a standard deviation as a reference and considering the autocorrelation of the bathymetric data (Verfaillie et al. 2007).

With these parameters defined, the calculations at the broad (BPI_{Bro}) and fine (BPI_{Fin}) scales of the geomorphological complexity model were done with equation (1):

$$BPI_x = Z_{Comp} - Z_{Comp\_Adjust\_x}, \quad (1)$$

where x is the scale (broad or fine), Z_{Comp} is the value of the complexity components (depth, slope, and aspect) of cell Z, and $Z_{Comp\_Adjust\_x}$ is the average value of the complexity components of the neighborhood cells within radius x (broad or fine) (Wilson et al. 2007).

Based on the BPI values obtained in the broad and fine scale models, each pixel of the DEM was classified into a zone or structure defined in a catalog with threshold values (Jerosch et al. 2015) (Table 1).

Cover of submerged aquatic vegetation (SAV)

The geospatial distribution patterns of SAV were analyzed in the western and central regions of the Yucatán coast (from Celestún to Dzilam de Bravo) (Fig. 1). The eastern region was not included in this analysis due to a red tide event (COFEPRIS 2011) that severely modified benthic communities, an impact documented in other regions (Lee et al. 2007), which made conditions incomparable with those of the rest of the study area.

The methodological approach for this study was regional in scale and employed standard techniques demonstrated to be effective for mapping benthic habitats and seascapes (Swanborn et al. 2022, Schenone et al. 2023). We used a stratified random sampling design, which has been reported to be optimal to map SAV, to define the sites to quantify SAV cover (Hirzel and Guisan 2002, Wilson et al. 2019). We used an unsupervised classification of 2 Landsat 7 ETM+ images (paths: 20 and 21; row: 45) from April 2010 as a basis and applied the K-means algorithm (15 distinct unsupervised classes). A total of 219 sampling sites were randomly distributed within each unsupervised class (Mastrantonis et al. 2024), considering a minimum separation distance of 90 m between sites (same design as Palafox-Juárez and Liceaga-Correa 2017). Following a modified method by Aronson and Swanson (1997), we obtained a 5-min underwater video transect at each site, with an orientation perpendicular to the bottom and at a distance of 80 cm, covering an approximate area of 50 m^2 (1 m wide × 50 m long).

Video analysis followed standard procedures for benthic community mapping and was performed at the functional group level (e.g., algae and seagrass), which has been recommended as an effective and efficient approach at the seascape scale (Roelfsema and Phinn 2010, Herkül et al. 2013, Leiper et al. 2014, Greenfield et al. 2016, Pygas et al. 2020). The Coral Point Count with Excel extensions (CPCe) application (Kohler and Gill 2006) was used, overlaying 20 random sampling points per frame, and 28 frames per video were analyzed, representing approximately one photograph every 1.78 m along the recorded transect (Díaz-Aguilar 2012, Palafox-Juárez and Liceaga-Correa 2017). For each of the 20 random points in each frame, the taxonomic group of the SAV present was identified: seagrass, green algae, red algae, brown algae or algal turf.

Influence of geomorphology on submerged aquatic vegetation (SAV)

A Bayesian multinomial logistic model (BMLM) with a nonlinear structure was generated to recognize the complex relationship between geomorphological variables (depth, slope, and aspect) and the presence of different taxonomic groups of SAV. Splines were used to model this relationship (cyclic splines were considered for the aspect, given its circular nature). From this model, we estimated the probabilities of presence for each SAV taxonomic group based on each of the geomorphological characteristics of the seafloor.

Table 1. Characteristics used in the morphological classification of the seafloor of Yucatán. Summary of the morphological characteristics and their values at the broad and fine scales (a bathymetric position index [BPI] value of 100 corresponds to one standard deviation) that define the morphological classification.

Geomorphological classification	Clase	BPI Broad scale		BPI Fine scale		Slope	
Zone		Lower	Upper	Lower	Upper	Lower	Upper
	Elevation	100					
	Plaine	–100	100				0.042
	Gentle slope	–100	100			0.042	
Structure							
	Land depression	–100	100		–100		0.042
	Submarine hills	–100	100	100		0.042	

For the zones defined in the broad-scale BPI model, we created a second BMLM that used the geomorphological zoning as the predictor variable; from this, we obtained estimates of the probability of presence for each SAV group for each zone.

To achieve probabilities that summed to 100%, in the 2 previous BMLM models, we considered the additional group "Other," which included the remaining non-plant elements (i.e., flagstone, rock, sand, and other organisms) at each random point in each frame. This analysis was not performed for structures due to their small area, which did not include a sufficient number of sampling sites for such an analysis. The BMLMs were constructed using the 'brms' package (Bürkner 2017, 2018) in R (R Core Team 2020).

Results

Bathymetric data collection

The 170 transects surveyed totaled 2,314 linear km sampled with the single-beam echosounder, which produced a total of 977,747 depth records after error correction. The longest transect (26.83 km) was recorded to the west, off the port of Celestún, and the shortest (7.42 km) was recorded to the east, off the port of El Cuyo (Fig. 1).

Geomorphological classification of the seafloor

Given the semivariance of the depth data, these were fitted to an isotropic Gaussian model (nugget = 0.01; plateau = 9.016; range = 12,903.78 m; R^2 = 0.967; *RSS* = 1.86), and a DEM spatial resolution of 40 m per pixel was defined, with a high cross-validation correlation (R^2 = 0.946) and a model prediction efficiency of 99.3%. This parameterization was essential for the repeatability and accuracy of the analyses presented here.

Depth (Fig. 2a) and slope (Fig. 2b) varied parallel to the coastline. The aspect showed the greatest variability in a direction perpendicular to the coast (Fig. 2c). Bathymetry was uniform longitudinally (E–W) and showed a consistent pattern latitudinally (N–S). A discrete slope with values less than one degree (<1°) predominated; this created a homogeneous plain with a predominant north–northwest aspect. Together, these features defined the geomorphological landscape of the shallow coastline studied (Fig. 2).

With the results of the BPI model and the definition of the geomorphological characteristics of the seafloor (Table 1), the study area was classified into 3 distinct zones (broad scale: elevation, plain, and gentle slope) and 2 types of structures (fine scale: submarine hills and depressions) (Fig. 3).

The section of the study area farthest from the coast, near the –12 m isobath, showed 3 depressions at both the broad and fine scales. These were classified as structures, together with 3 submarine hills or isolated elevations (Fig. 3), of which the one located in Celestún had unique morphological characteristics.

Effect of geomorphology on submerged aquatic vegetation (SAV)

The most abundant SAV species on the western coast of Yucatán were (in descending order) seagrasses (mainly *Thalassia testudinum*, although *Syringodium filiforme* and *Halodule wrightii* were also recorded), green algae (Chlorophyta), red algae (Rhodophyta), brown algae (Phaeophyta), and algal turf (a mixture of juvenile macroalgae, fast-growing filamentous species, brown algae, green algae, and cyanobacteria) (Fig. S1).

Geomorphological components (depth, slope, and aspect) had varying degrees of influence on the probability of presence of SAV taxonomic groups (Fig. 4). Based on the first BMLM (Table S1), depth was identified as the most important variable in determining the presence of SAV taxonomic groups on the western coast of Yucatán.

Seagrasses were distributed in areas with depths less than –5 m (Fig. 4a) and their presence markedly changed with increasing depth. The distribution area of seagrasses (Fig. S1) showed few variations with the slope and aspect variables; therefore, the influence of these variables was minimal (Fig. 4b, c).

Green algae were primarily distributed in areas with depths between 5 and 7 m (Fig. 4d) and on steeper slopes (Fig. 4e), and aspect was not an important factor in explaining their presence (Fig. 4f). On the other hand, red algae showed association patterns with the 3 geomorphological variables and were mainly distributed in the deeper areas, with steeper slopes (Fig. 4h) and a northerly aspect (Fig. 4i). Finally, brown algae had a lower presence than red algae but a similar distribution (Fig. 4j–l). Algal turf was mainly distributed in areas with depths greater than 2.5 m (Fig. 4m), low slopes (Fig. 4n), and a northerly aspect of the seafloor (Fig. 4o).

With the second BMLM, whose explanatory variable was geomorphological zoning, we identified that the elevation zone had the highest seagrass cover (39.7%), followed by green algae (19%), algal turf (14.5%), red algae (10.3%), and brown algae (2.6%). This zone had the highest diversity and presence of SAV taxonomic groups (seagrass, green algae, algal turf, red algae, and brown algae); for the zones identified as plains and gentle slopes, the presence of algal turf dominated, although seagrass, green algae, and red algae were also present (Table 2).

Discussion

Mapping the seascape

Several conceptual approaches and recent studies have promoted the use of varied methodologies and technologies, with different spatial and grain size extensions, to study biodiversity across marine assemblages at the landscape scale, where benthic biodiversity is assessed at the functional group level (Gladstone-Gallagher et al. 2019). This scale allows addressing the heterogeneity of systems

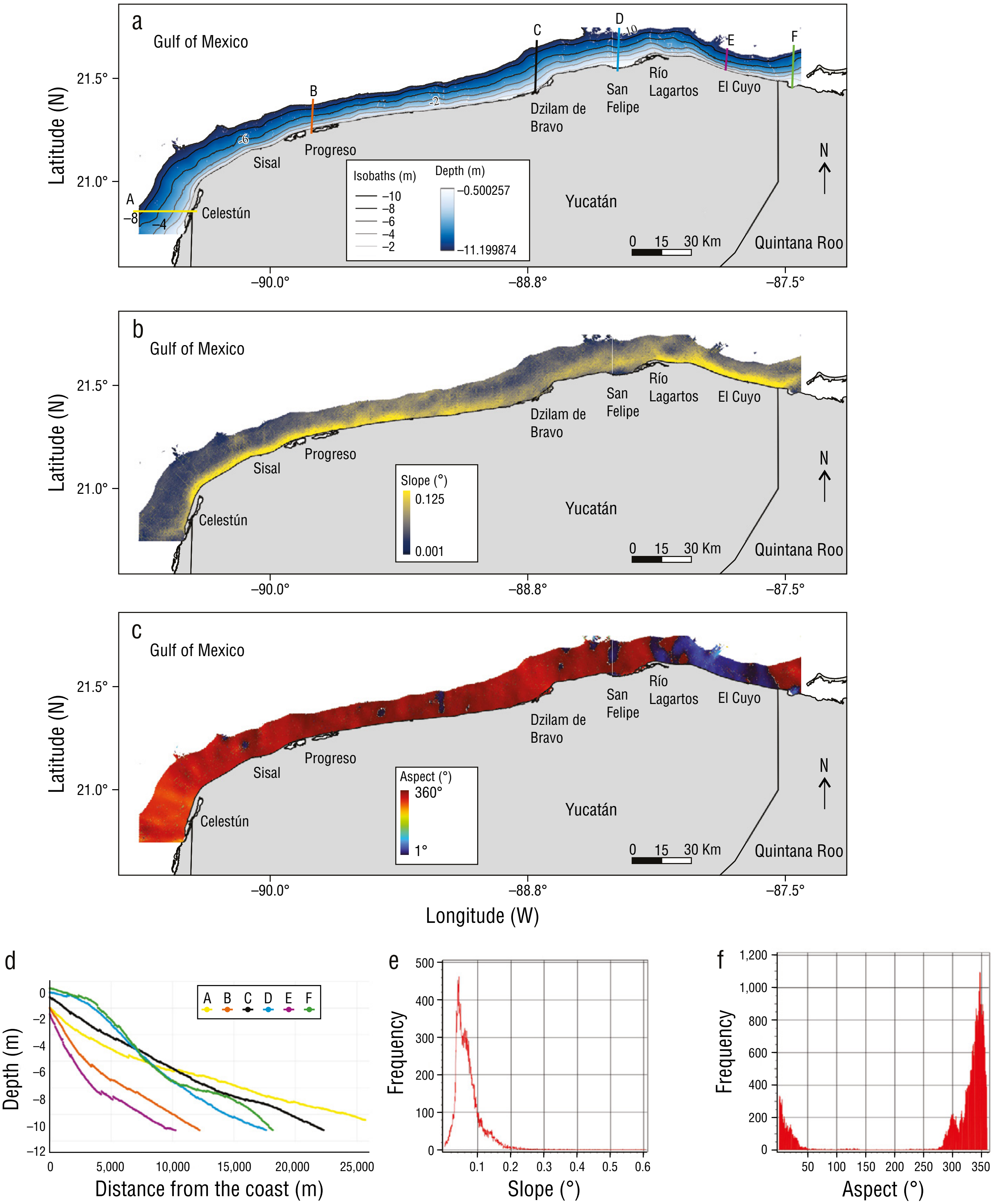

Figure 2. Representation of component variables of the geomorphology of the shallow coastline of the northern Yucatán Peninsula. From the digital elevation model (DEM) (**a**), seafloor slope (**b**) and aspect (**c**) were calculated. Depth profiles (**d**) indicated in (**a**) are shown, along with the frequencies of slope (**e**) and aspect (**f**) values.

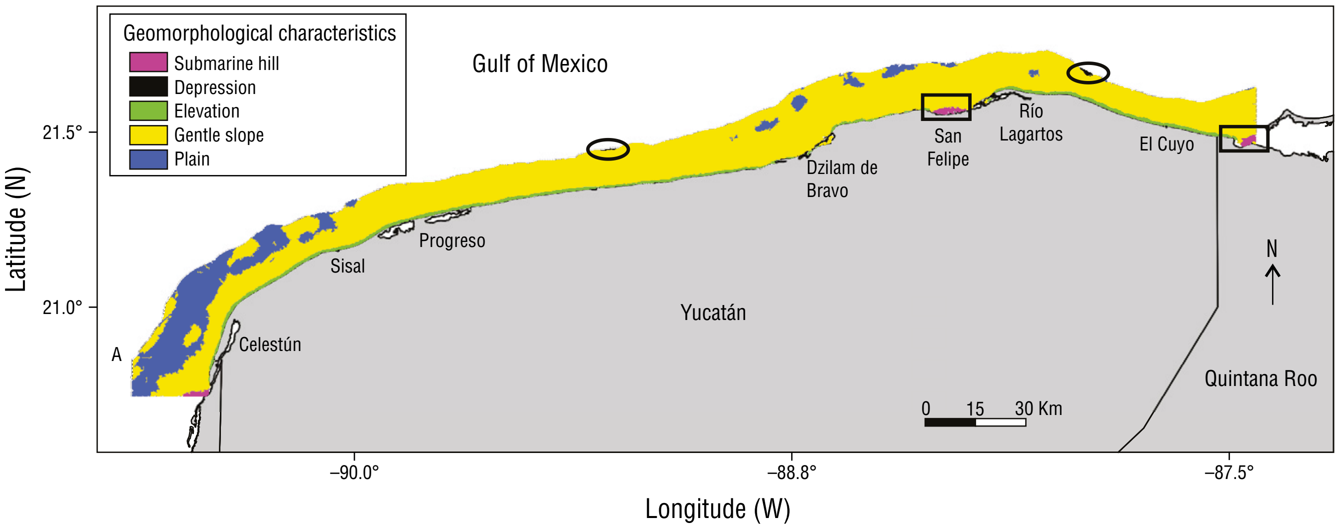

Figure 3. Geomorphological features of the surface of the nearshore seafloor of Yucatán; submarine hills, within squares, and depressions, within ellipses, are notable.

within a landscape, including groups with different biotic and abiotic requirements, functional redundancy, and varied responses to stressors, which is essential to understand ecological resilience and identify potential indicator groups of ecosystem processes (Kaskela et al. 2017, Brunier et al. 2020, Pygas et al. 2020, Swanborn et al. 2022).

In this context, the exponential growth of geographic information technologies (GIT), the development of geomatic analysis techniques, and the integration of multiscale observation platforms have enabled notable advances in the physical characterization of the seafloor and associated benthic communities (Schenone et al. 2023). Spatial products derived from these assemblages have fostered interdisciplinary methodologies and contributed to the establishment of comparable baselines in landscape analyses, even at interdecadal scales. Operational monitoring initiatives in the Baltic Sea, the Pacific Ocean, and other regions in Europe have implemented similar approaches with multiscale data (Kaskela et al. 2017, Hao et al. 2023).

The geomorphology of the seafloor, particularly in shallow regions such as the northern coast of Yucatán, tends not to experience abrupt changes, even after severe hydrometeorological events. For example, Cuevas et al. (2013a) documented submarine dune movements in some of the areas analyzed in this study and reported variations of only 3 to 10 m over more than 25 years. Therefore, the geomorphological information presented is considered to retain its temporal validity.

Two of the identified structures, Actam Chuleb and Punta Caracol, had been previously described (Cuevas et al. 2013b). The present study reports for the first time a third submarine hill in Celestún and 3 depressions around the –12 m isobath, which represents an original contribution to the understanding of the submarine relief of the region. These structures are particularly relevant because they are associated with submarine dune complexes that shift and shape the landscape with their associated seagrass communities and macroalgal forests (Cuevas et al. 2013a).

General ecological patterns of submerged aquatic vegetation (SAV)

Current spatial patterns of the SAV could differ from those observed at the time of the study due to ecological dynamics of the landscape; nonetheless, the ecological relationships described are assumed to remain representative. This is because the geomorphological complexity of the seafloor operates at broader temporal scales, which provides a relatively stable framework for the analysis of biotic associations.

The shallow coast of Yucatán is characterized by low topographic complexity, where zones of plains and gentle slopes, characteristic of the Campeche Bank, are clearly distinguishable. These are easily identifiable with the thresholds defined for each differentiating element in the BPI (Wright et al. 2012). Appendini et al. (2012) identified a critical strip for sediment transport between the 0 and –3 m isobaths, which coincides with the elevated zone identified in this study and is associated with a shallow strip close to the coastline, where unconsolidated sediment accumulates due to dynamics associated with those of the coastline.

The link between geomorphological features and biological communities is key to understanding the structure and functioning of ecosystems (Ordines et al. 2011). In the present study, depth was the variable most strongly associated with the presence of SAV, which is expected from

Table 2. Probability of presence for each group of submerged aquatic vegetation (SAV) in each of the identified geomorphological zones. Probability values estimated from the Bayesian multinomial logistic model (BMLM) with these zones as the explanatory variable. “Others” includes non-plant elements that do not correspond to a main taxonomic group of the SAV (e.g., flagstone, rock, sand, and other organisms); “Other” is included to show that the probabilities of presence add up to 100% in each geomorphological zone.

Zone	SAV Group	Probability of presence (%)	Credibility interval of 95%	
	Seagrass	39.7	38.2	41.1
	Green algae	19	17.9	20.2
	Red algae	10.3	9.4	11.2
Elevation	Brown algae	2.6	2.2	3.1
	Algal turf	14.5	13.5	15.6
	Other	13.9	12.9	14.9
	Seagrass	8.2	7.4	9.2
	Green algae	7.7	6.9	8.6
	Red algae	4.1	3.5	4.8
Plain	Brown algae	6.5	5.7	7.3
	Algal turf	13.8	12.7	14.9
	Other	59.7	58.1	61.3
	Seagrasses	3.9	3.6	4.4
	Green algae	10.2	9.7	10.8
Gentle slope	Red algae	11.1	10.5	11.7
	Brown algae	4.9	4.4	5.2
	Algal turf	27.1	26.3	27.9
	Other	42.8	41.9	43.7

an ecological perspective. However, we also documented the estimated distribution of SAV using geomorphological categories, as well as certain assemblage patterns, constituting a unique contribution for the southeastern Gulf of Mexico.

In their review of more than 50 studies on the influence of bottom morphology on benthic communities, Pygas et al. (2020) noted that the relationship between geomorphological complexity and the distribution of macroalgae has been scarcely studied. In this sense, both Pygas et al. (2020) and Kaskela et al. (2017) agreed on the relevance of the BPI to evaluate associations of morphological complexity with the distribution of benthic communities, demonstrating its effectiveness to identify suitable habitats for invertebrate organisms. Likewise, Kaskela et al. (2017) suggested that applied logistic models are robust tools to evaluate interactions between geomorphological variables and functional groups, and highlighted the influence of roughness, substrate variability and slope as key characteristics in the distribution of benthic communities.

Documenting and validating local patterns of association between SAV and seafloor features strengthens tools for assessing landscape changes following extreme events (e.g., hurricanes or red tides), or simply for multitemporal comparisons. Numerical functions derived from these associations allow geomorphological features to be used as surrogate variables for ecological inferences (Kaskela et al. 2017), as has been done for microtopography (Schenone et al. 2024) and sediment geomorphology (Brunier et al. 2020).

Despite progress, Kaskela et al. (2017) noted the need for additional studies to clarify the relationships between geomorphology and benthic communities, as ambiguities still prevail. In line with this, this study highlights the urgency of conducting analyses at higher ecological resolution, including in situ measurements of key physicochemical variables such as salinity, temperature, and transparency, which, together with geomorphology, govern the spatiotemporal distribution of SAV.

Implications for the management of the seascape in Yucatán

This work represents the first systematic categorization of the geomorphological complexity of the seafloor off the northern coast of the Yucatán Peninsula, establishing a

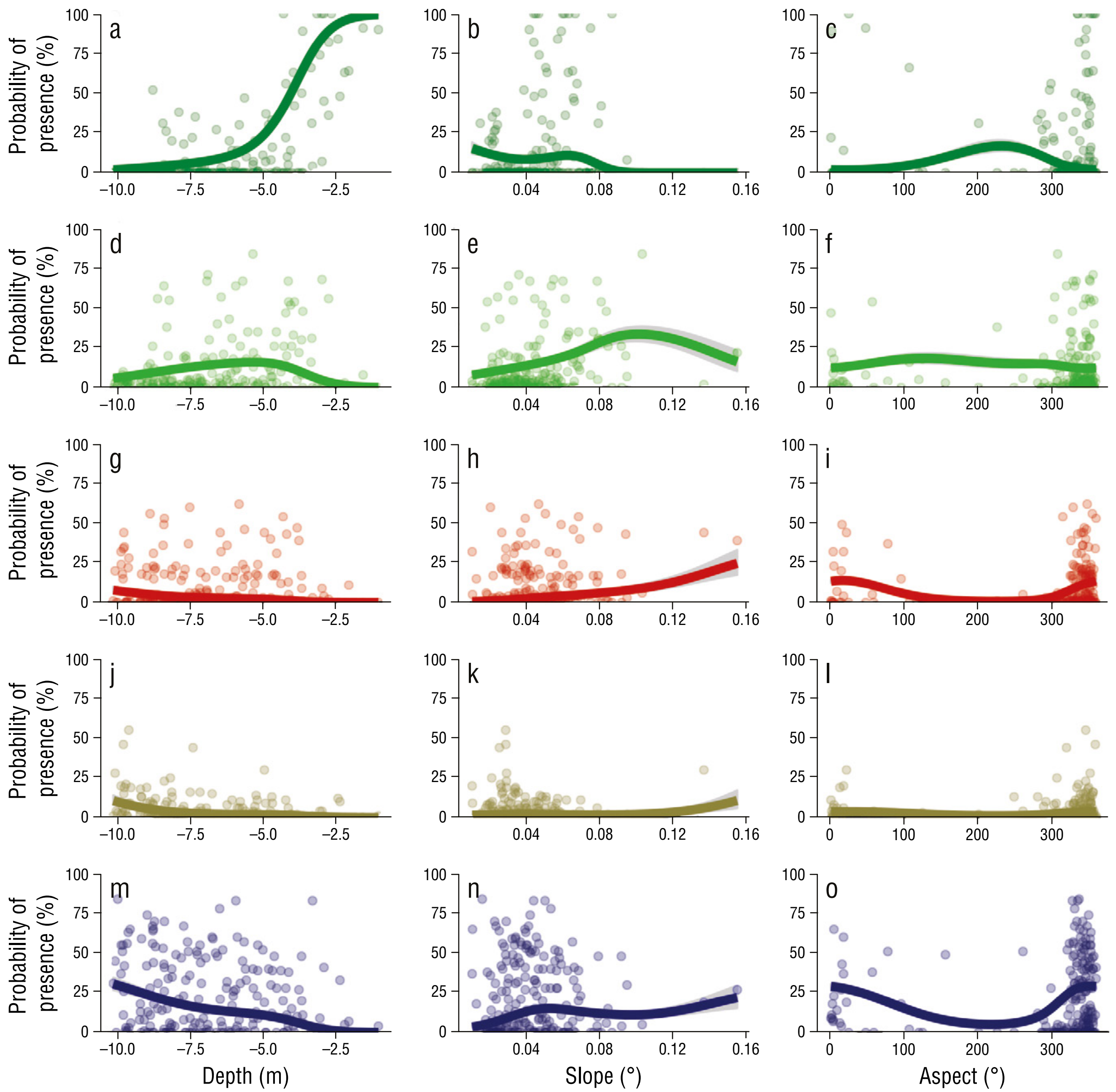

Figure 4. Estimated nonlinear relationships (curves) between geomorphological variables (*x*-axis) and the probability of presence (*y*-axis) of the 5 most abundant taxonomic groups of submerged aquatic vegetation on the west coast of the Yucatán Peninsula. The gray bands correspond to the confidence bands associated with the estimates of the adjusted multinomial logistic additive Bayesian model. Geomorphological variables: depth (left), slope (center), and aspect (right). Taxonomic groups: seagrasses (dark green), green algae (green), red algae (red), brown algae (brown), and algal turf (dark blue). The points correspond to field observations.

baseline for oceanographic, biological, and ecological studies in southeastern Mexico. Furthermore, it expands the knowledge of the Yucatán shallow coast and contributes to the understanding of processes such as hydrodynamics (Qian et al. 2020), sediment transport (Appendini et al. 2012), and ecological functioning (Wedding et al. 2008, Palafox-Juárez and Liceaga-Correa 2017), which are fundamental for decision-making regarding coastal development, adaptive management, and environmental conservation.

In addition, this study retrieves and makes publicly available a bathymetric database that includes SAV distribution data from over 14 years ago. This collection constitutes a critical reference for studies of landscape change, particularly in the face of pressures such as oil spills, infrastructure construction, harmful algal blooms, or the effects of climate change (Lotze and Worm 2009, Wilkinson et al. 2011, Hawkins et al. 2013, Thurstan et al. 2015, Bledsoe et al. 2022). Its availability and analysis promote evidence-based management and strengthen the ecological and social resilience of the Yucatecan coast.

Conclusions

The statistical and spatially explicit results in this study confirmed the ecological process documented at other latitudes regarding the influence of geomorphological complexity on the distribution of benthic communities, especially SAV. The geographic and ecological scope and scales addressed in this study provide opportunities for comparative analysis at the community and seascape levels, contributing strategic elements for the territorial management of the study area.

The complex landscape of the Yucatán Shelf is unique due to its size and low change rate in its slope, which create a vast marine territory where diverse interests and vocations associated with the benthic marine landscape coexist. This reinforces the need to implement management strategies based on scientific information and provide full legal certainty to ensure the provision of services from these ecosystems to oceans in general and, in particular, to the population of Yucatán.

English translation by Claudia Michel-Villalobos.

Declarations

Supplementary material

The supplementary material for this work can be downloaded from: https://www.cienciasmarinas.com.mx/index.php/cmarinas/article/view/3458/420421220.

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Conflict of interest

The authors declare they have no conflict of interest.

Author contributions

Conceptualization: MAL-C, EC; Data curation: LAR-S, HH-N, EBP-J, EC; Formal analysis: MAL-C, EJG, LAR-S, HH-N, EBP-J; Funding acquisition: MAL-C, EC; Research: MAL-C, EJG, LAR-S, EBP-J, EC; Methodology: MAL-EC, LAR-S, EBP-J, EC; Resources: MAL-C, EC; Software: EJG, HH-N, LAR-S; Supervision: MAL-C; Validation: EC, EJG; Visualization: EC; Writing—original draft: MAL-C, EJG, EBP-J, EC; Writing—review and editing: LAR-S, HH-N.

Data availability

The data for this study are available from the corresponding author by reasonable request.

Use of AI tools

The authors did not employ any AI tools in this work.

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