Climate Change Risk Scenarios for *Echinometra lucunter* (Linnaeus, 1758) in the Colombian Caribbean

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Article

Climate Change Risk Scenarios for *Echinometra lucunter* (Linnaeus, 1758) in the Colombian Caribbean

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Abstract

Echinometra lucunter (Linnaeus, 1758) is a sea urchin widely distributed throughout the Caribbean, recognised for its pivotal ecological role as a bioindicator. Its niche is characterised by herbivory within coral reef frameworks and shallow rocky substrates, where it significantly contributes to nutrient cycling and net primary productivity across Caribbean marine ecosystems. However, anthropogenic climate change poses a substantial threat to its populations, specifically through perturbations in marine hydrochemistry. This study aims to estimate and analyse the habitat suitability of *E. lucunter* in the Southwestern Caribbean under current conditions and future climate risk scenarios. To achieve this, we employed ecological niche modelling (ENM) using an ensemble forecasting approach that integrates multiple algorithms, including Maximum Entropy (MaxEnt), Generalized Linear Models (GLM), and Random Forest (RF). Models were calibrated using physical and chemical oceanographic variables and projected onto two contrasting climate pathways (SSP1-1.9 and SSP5-8.5) for the 2040–2050 horizon. Our results indicate that while the contemporary distribution of the species is strongly dictated by physiographic factors—such as bathymetry and coastal proximity—biogeochemical variables, including pH fluctuations, sea surface temperature (SST), and chlorophyll-a net productivity, are the primary drivers of habitat suitability shifts. Both future scenarios project a marked niche contraction, characterized by severe loss of core habitat and a high risk of local extirpation. Conversely, specific insular and coastal regions in Colombia may serve as climate refugia, suggesting a potential buffering effect against regional declines. In conclusion, *E. lucunter* emerges as a species highly vulnerable to climate-driven stressors, underscoring the urgent requirement for spatially explicit conservation strategies within the Caribbean basin.

Keywords: climate change; climate refugia; Caribbean Sea; *Echinometra lucunter*; ecological niche modelling (ENM); habitat suitability; marine conservation; ocean acidification

1. Introduction

Sea urchins (Echinoidea) are model organisms in studies of developmental embryology, environmental health, and marine ecology. Due to their wide geographic distribution and relatively rapid reproductive cycles, these echinoderms serve as effective bioindicators of the state of coastal ecosystems. *Diadema antillarum* and *Echinometra lucunter* are the two most representative species in the Caribbean and occupy key ecological functions in the niche they occupy as primary herbivores on coral reefs and rocky substrates.

Part of the potential for bioindication, echinoids herbivory has spatial partitioning on feeding habits but rather a spatially partitioned one (Carpenter et al., 1986) and show density dependend suze regulation that tell about their fecundity status and survorship (Levitan et al., 1989, Lessios et al., 1984) generating mosaics of differential pressure on the benthos.

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The spatial partitioning of grazing determines the structure of other species such as algal communities, and modulates the availability of substrate for coral recruitment (Ogden et al., 1973, McClanahan et al., 2011). Consequently, the regulation of macroalgae by sea urchins not only reduces competition for space and light, but also directly influences reef resilience.

The functional importance of these herbivores was dramatically demonstrated following the mass mortality of *D. antillarum* in the Caribbean (Lessios et al., 1984), an event that caused macroalgal proliferation and profound alterations in benthic dynamics, effects that were subsequently documented in recovery processes and the persistence of alternative states (Edmunds and Carpenter, 2001).

Echinometra lucunter, as an allogenic engineer of the ecosystem, has a high bioerosion capacity that can modify the topography of the carbonate substrate, generating cryptic microhabitats that serve as refuge for multiple associated taxa (Borrero-Pérez et al., 2012; Hendler, 1995). However, disproportionate increases in its population density can intensify biogenic erosion and alter the proportion of calcifying substrates, compromising the structural integrity of the reef.

Some studies have shown that processes linked to echinoids, such as their biomass and predation on them, have critical thresholds along fishable biomass gradients, preceding a substantial decline in coral cover (McClanahan et al., 2011). Complementarily, recent chronic disturbances, such as massive *Sargassum* strandings, have been documented to induce restructuring in the breadth and overlap of the trophic niche of Caribbean echinoids, promoting functional convergence under conditions of persistent environmental stress (Cabanillas-Terán et al., 2025). Taken together, these findings suggest that the population and functional dynamics of *E. lucunter* can be integrated into nonlinear sequences of ecosystem change, particularly in contexts where multiple pressures—trophic and environmental cues—interact simultaneously.

Consequently, current demographic imbalances, combined with the absence of robust predictive frameworks for accelerated climate change, represent a significant challenge for the management and conservation of coral ecosystems.

In the Neotropics, the conservation status of *E. lucunter* is increasingly threatened by environmental stressors, specifically rising sea surface temperatures (SST) and fluctuations in pH and salinity. These factors induce chronic physiological stress on urchin populations and propagate cascading effects throughout the marine food web. To preserve this species and its associated ecosystem services, it is imperative to quantify the impacts of these stressors on its habitat suitability (Deucher et al., 2024).

This study estimates and analyzes the habitat suitability of *E. lucunter* across the Caribbean basin under critical climate change projections. To achieve this, we employ ecological niche modeling (ENM) frameworks grounded in the Hutchinsonian niche concept (Hutchinson, 1957). These approaches allow for the approximation of the species' environmental envelope based on relevant abiotic predictors, providing an operational representation of its realized niche under current and projected climatic conditions. Such methodologies are essential for predicting, quantifying, and spatially delineating distributional shifts in species of high conservation relevance (Cruz-Román, 2024).

The results are intended to inform adaptive management strategies in marine and coastal ecosystems, considering the functional role of *E. lucunter* within reef dynamics. By projecting potential distributional changes under future climate scenarios, this research contributes to evidence-based policy development aligned with Sustainable Development Goals 13 (Climate Action) and 14 (Life Below Water), as well as commitments established under the Paris Agreement (UN, 2015).

2. Materials and Methods

2.1. Occurrence Data

To acquire the occurrence records required for the modeling framework, the Global Biodiversity Information Facility (GBIF) database was queried on May 20, 2025 (GBIF.org User, 2025). The

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resulting dataset underwent a rigorous data cleaning and curation process. We filtered for "presence-only" records, systematically removing duplicate and inconsistent coordinates. To ensure temporal alignment with contemporary oceanographic datasets, only observations from the year 2000 onwards were retained.

To mitigate the effects of sampling bias—a common artifact in opportunistic biodiversity data—we implemented spatial thinning (spatial subsampling). A minimum threshold distance of 1 km was maintained between adjacent points to reduce spatial autocorrelation and prevent model over-fitting (Hijmans & Elith, 2023). This process yielded a final dataset of 54 high-quality presence records spanning four Caribbean countries: Colombia, Panama, Costa Rica, and Nicaragua. These nations were selected based on their oceanographic connectivity and the availability of robust, validated data (Figure 1).

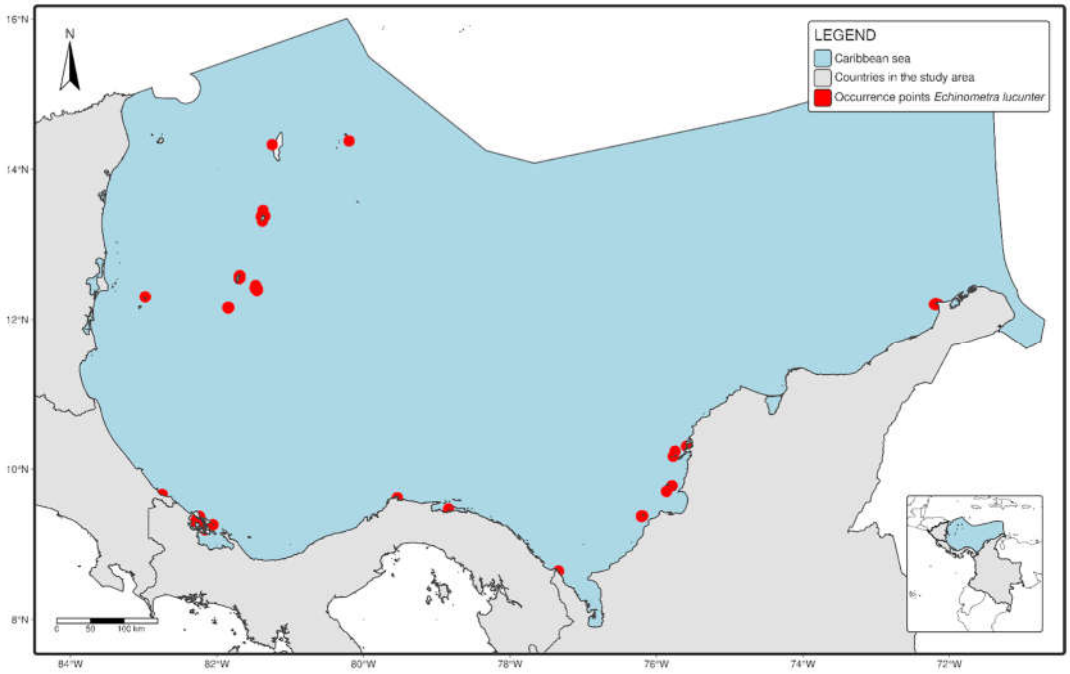

Figure 1. Geographic distribution of occurrence records for the rock-boring urchin *Echinometra lucunter* within the Southwestern Caribbean study area. These points represent the post-processed presence data utilized for ecological niche modeling (ENM) after applying spatial thinning and quality filters.

2.2. Processing of Contemporary Oceanographic Variables

In this investigation, 19 oceanographic variables were sourced from the MARSPEC and Bio-ORACLE databases. The first dataset (MARSPEC) comprises annual mean observations from the late 20th century at a spatial resolution of approximately 1 km near the equator. Conversely, the Bio-ORACLE layers encompass the 2010–2020 period with a resolution of roughly 5.5 km near the equator (Assis et al., 2024; Sbrocco & Barber, 2013). Despite these temporal discrepancies, it is assumed that they represent mean climatic conditions suitable for characterizing the contemporary niche of the species. The study area was delineated by merging the Exclusive Economic Zone (EEZ) polygons of the Caribbean territories for each involved country: Colombia, Panama, Costa Rica, and Nicaragua. These vector layers were downloaded from the Marine Regions portal (Flanders Marine Institute (VLIZ), Belgium, 2023).

Subsequently, the rasters were resampled to a 30 arc-second resolution (~1 km) using bilinear interpolation, and environmental masks were applied to all oceanographic layers based on MARSPEC bathymetry, previously constrained to depths not exceeding 50 meters. This procedure, coupled with the high resolution of the bathymetric data, effectively captures the distribution of the

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sea urchin, which is exclusively reported in nearshore, wave-exposed environments (Deucher et al., 2024; Hendler, 1995).

Predictor selection was conducted via a Pearson correlation analysis using the terra package (version 1.8-54) in the R environment, which facilitated the manipulation of most spatial data throughout this study (Hijmans, 2020). Based on the results of the correlation matrix, one predictor from each pair exhibiting a coefficient $|r| > 0.7$ was discarded. Furthermore, multicollinearity among the oceanographic variables was addressed by calculating the Variance Inflation Factor (VIF), discarding variables with significant multicollinearity (VIF > 5). These are critical steps, as highly correlated variables or those exhibiting high multicollinearity contribute redundant information to the models and may introduce noise, leading to model overfitting (Zhang et al., 2025).

As a final selection criterion, only variables of demonstrated ecological importance for *Echinometra lucunter* in the Caribbean Sea were retained, resulting in 8 oceanographic variables for model calibration (Table A1).

Finally, utilizing the 8 environmental variables, 540 background points were randomly generated at a 1:10 ratio (10 background points per occurrence), which underwent spatial thinning (spatial subsampling) identical to the occurrence data. Background points serve to characterize the available environment for *E. lucunter*; this method does not assume absence but rather facilitates the Maximum Entropy (MaxEnt) algorithm's comparison of available habitat against actual occurrences. In contrast, other statistical and machine learning models require pseudo-absences; therefore, 54 pseudo-absences were generated within the study area with a minimum separation of 2 km (Hijmans & Elith, 2023).

2.3. Processing of Future Oceanographic Scenarios

To predict the habitat suitability of *E. lucunter* under climate change scenarios, environmental variables available from the Bio-Oracle database were utilized. Bathymetry, distance to the shore, and concavity metrics were held constant, as MARSPEC does not provide oceanographic layers projecting future conditions (Assis et al., 2024; Sbrocco & Barber, 2013).

Scenarios were modeled under two Shared Socioeconomic Pathways, SSP1-1.9 and SSP5-8.5. The former represents an optimistic or sustainability-oriented scenario aligned with the Paris Agreement (2015), which proposes a significant reduction in greenhouse gas emissions. In contrast, expectations for SSP5-8.5 are considered pessimistic, as they forecast increasing greenhouse gas emissions with minimal mitigation efforts.

The raster layers corresponding to future oceanographic data were resampled, clipped, and masked following the same protocols applied to current variables, as detailed in section 2.2 of this article.

2.4. Model Calibration, Evaluation, and Ensemble Forecasting

Each algorithm possesses inherent strengths and weaknesses; consequently, the literature highlights the extensive use of ensemble modeling to enhance the precision of potential distribution predictions. Various tools are employed to facilitate this task (Bruce et al., 2020; Gbadamassi et al., 2025; Zhang et al., 2025). Within the framework of this research, a fine-tuning of the data and a more granular control of the modeling process were required; therefore, models were executed individually, and the results were subsequently assembled. The procedure involved four algorithms: Maximum Entropy (MaxEnt), Generalized Linear Models (GLM), Generalized Additive Models (GAM), and Random Forest (RF).

For MaxEnt, the "ENMevaluate" function from the ENMeval package (version 2.0.5.2) was utilized in the R environment to identify the optimal fit. This method consists of training multiple models under different hyperparameters (Kass et al., 2014). To select the most parsimonious result, the Corrected Akaike Information Criterion (AICc) was considered, prioritizing the lowest value (Bruce et al., 2020).

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Subsequently, using the environmental predictors for presence points (1) and pseudo-absences (0), GLM and GAM were trained using a binomial distribution. The Random Forest algorithm was executed with 500 decision trees and 2 variables sampled per split. These models were run using R base functions (GLM), the mgcv package version 1.9-3 (GAM), and the randomForest package version 4.7-1.2 (Breiman et al., 2002; Wood, 2000). All models were evaluated via k-fold cross-validation (k = 5), measuring fit quality with metrics such as Area Under the Curve (AUC) ≥ 0.9 and True Skill Statistic (TSS) ≥ 0.7 (Figure 2).

These evaluation methods serve as benchmarks for determining the reliability of the models' predictive capacity. The AUC metric ranges from 0 to 1, where 0.5 indicates performance no better than chance, while values approaching 1 reflect perfect discrimination between presences and absences. Conversely, the TSS range extends from -1 to 1, where values ≤ 0 represent random data (Zhang et al., 2025).

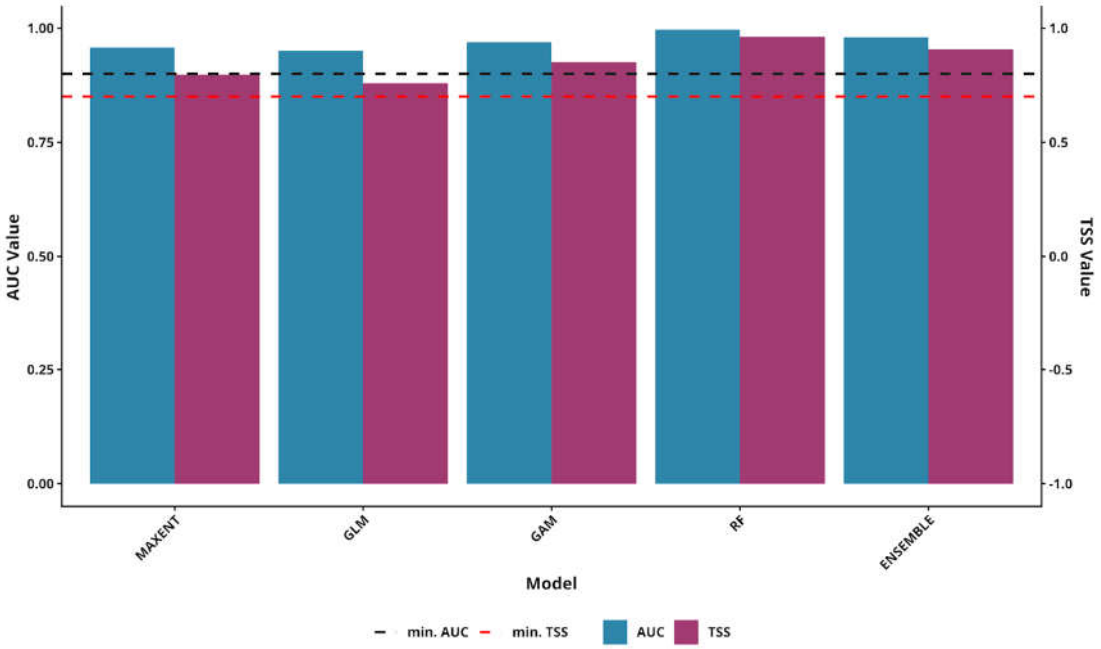

Figure 2. Area Under the Curve (AUC) and True Skill Statistic (TSS) values for the predictive models. The dashed horizontal lines intersecting the bars represent the minimum selection thresholds established for each respective evaluation metric.

Following the calibration process, final predictions were generated using a weighted average ensemble technique. In this approach, normalized weights were assigned based on True Skill Statistic (TSS) performance, as this metric effectively penalizes both omission and commission errors and remains independent of species prevalence. Consequently, higher TSS values correspond to a greater proportional influence within the final ensemble. While individual models assign specific importance to each predictor, this study prioritizes the ensemble output; thus, the focus remains on identifying the variables that best explain the niche of *E. lucunter* in the final model. This is illustrated in Figure 3, which was derived using the permutation importance method.

The prediction outputs are expressed as the probability of species presence, hereafter referred to as habitat suitability. This probability is mapped at the pixel level and stored in three raster (TIFF) files: one representing contemporary conditions and two projecting future scenarios, SSP1-1.9 (optimistic) and SSP5-8.5 (pessimistic). Final cartographic visualizations were generated using the tmap package (version 4.1) in R (Tennekes, 2014).

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2.5. Estimation of Habitable Area for E. lucunter

To quantify the suitable area, the suitability maps were binarized using the optimal TSS threshold; pixels with suitability values below this threshold were classified as "unsuitable," while those equal to or exceeding it were categorized as areas of potential presence. This calculation was performed for each scenario and disaggregated by country, with the total area expressed in km^2. To facilitate the visualization of differences across several orders of magnitude, areas are represented as log(km^2 + 1), while values reported within the text correspond to actual areas in km^2.

These results were supplemented by net change maps for the two future scenarios. Subsequently, suitability data were transformed and normalized following the methodologies described by Rödder & Engler (2011). This allowed for the calculation of ecological niche overlap within geographic space (G-space). The analysis was based on two overlap metrics: Schoener's D and the modified Bray-Curtis (BC) dissimilarity, implemented via the sdm package (Table A2). For these metrics, a value of 0 indicates a total lack of similarity, whereas a value of 1 represents maximum niche similarity (Naimi & Araujo, 2016; Schoener, 1968).

3. Results

3.1. Relative Importance of Oceanographic Variables

As illustrated in Figure 3, variables corresponding to distance from the shore and bathymetry collectively account for 52% of the niche explained by the model. These predictors represent the physiographic and topographic conditions of the study area, which remained constant during extrapolation across climate change scenarios (see Section 2.3). Conversely, pH range exhibited a significant importance of 28.1%, followed by temperature range (7.8%) and mean chlorophyll-a (7.5%). Together, these biogeochemical drivers contribute over 40% to the model's predictive power.

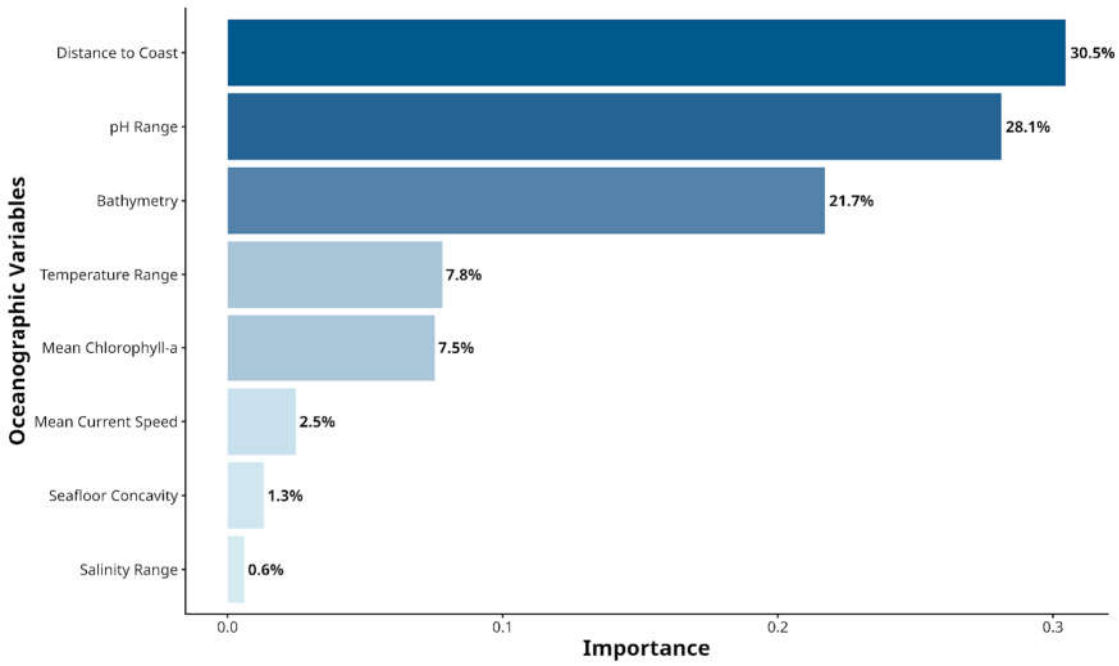

Figure 3. Importance of variables for the ecological niche model of *E. lucunter*.

3.2. Habitat Suitability and Climate Change Projections

Habitat suitability projections for *E. lucunter* under contemporary conditions reveal a clearly defined spatial gradient throughout the study area (Figure 4A). The highest probabilities of occurrence are concentrated in shallow coastal zones, while suitability progressively declines toward

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offshore and deeper environments. In deep oceanic sectors, habitat suitability is consistently negligible. At a regional scale, high-suitability zones are predominantly identified in Panama and Colombia, whereas Costa Rica and Nicaragua exhibit relatively smaller areas with elevated suitability values.

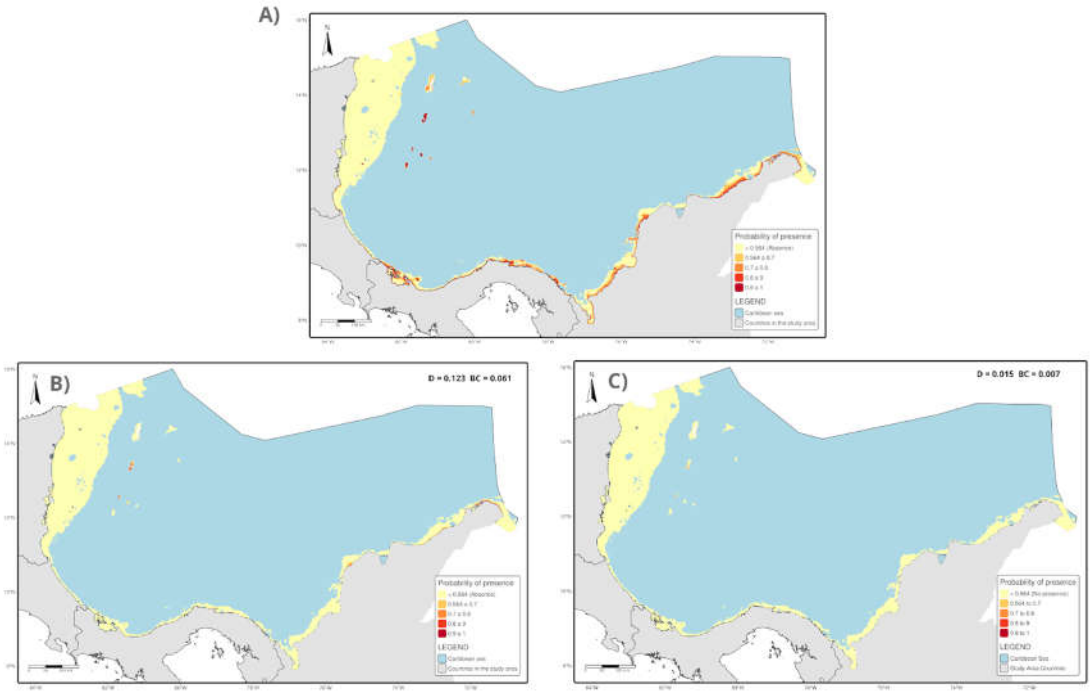

Figure 4. Habitat suitability projections for *E. lucunter* in the Caribbean Sea under contemporary conditions and future climate change scenarios. (A) Current scenario (2010–2020); (B) optimistic scenario SSP1-1.9 (2040–2050); and (C) pessimistic scenario SSP5-8.5 (2040–2050), focusing on the coastal sectors of Colombia, Panama, Costa Rica, and Nicaragua.

Projections for the most optimistic scenario, SSP1-1.9, reveal substantial reductions in the area originally available for the sea urchin. This contraction is supported by low niche overlap values, specifically Schoener's D (D = 0.123) and Bray-Curtis (BC = 0.061). The most severely impacted regions correspond to Nicaragua and Costa Rica. Although Colombia and Panama exhibit declines in habitable area for *E. lucunter*, these countries still retain specific coastal and insular zones with a high probability of occurrence.

In contrast, the pessimistic SSP5-8.5 scenario shows considerably more severe losses in original habitat suitability, reflected in critically low niche overlap values (D = 0.015; BC = 0.007). Under this scenario, few areas with a high probability of presence are identified, with notable exceptions in sectors of Colombian territory, such as the San Andrés and Providencia archipelago and the Guajira region.

3.3. Habitable Area for E. lucunter

Figure 5A presents the suitable habitat areas (km^2) on a logarithmic scale. Under contemporary conditions, Colombia possesses the greatest extent of suitable habitat among the four evaluated countries, with 7,213.72\ km^2 available. This is followed by Panama with 3,475.25\ km^2. Conversely, Nicaragua (331.23\ km^2) and Costa Rica (250.84\ km^2) exhibit considerably smaller spatial extents.

Regarding shifts in the marine extent available for the urchin, no gains were identified across any of the projected scenarios. As evidenced in Figure 4A and the net change maps (5B and 5C), the ensemble projected exclusively patterns of habitat loss and stability throughout the study area.

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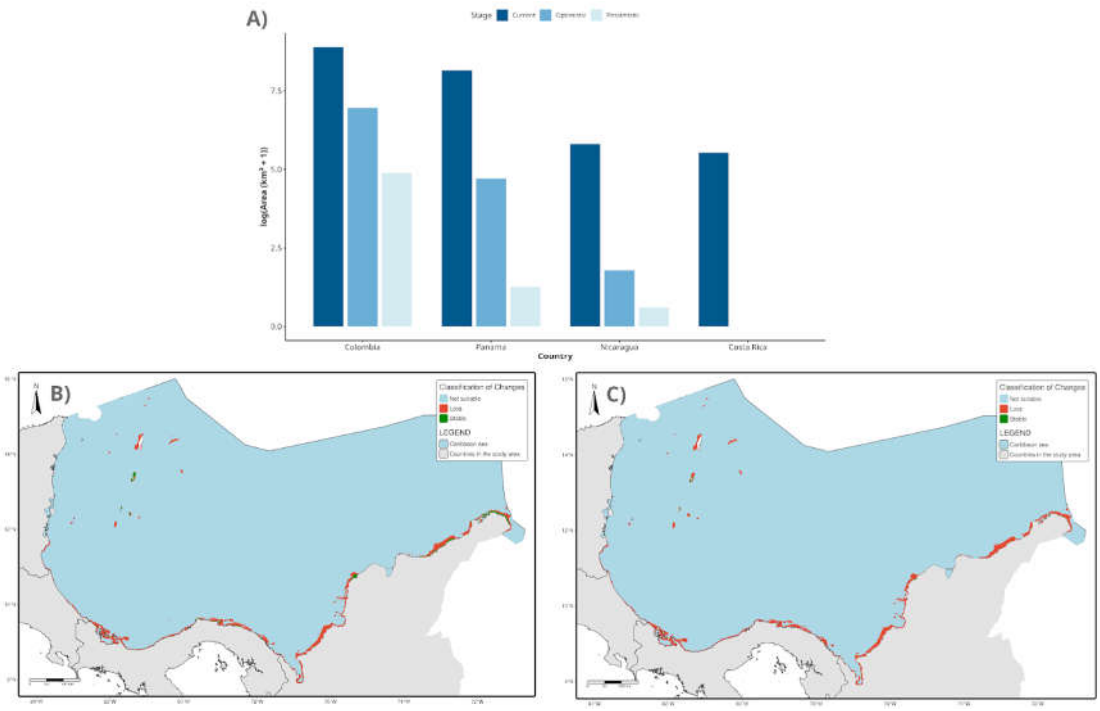

Figure 5. Shifts in habitat suitability for *Echinometra lucunter* under climate change scenarios in the Caribbean Sea. A) Total suitable habitat area (km^2) for contemporary conditions and future scenarios, represented on a logarithmic scale and disaggregated by country. B) Net change map of habitat suitability under the optimistic SSP1-1.9 pathway (2040–2050), highlighting regions of habitat loss and stability relative to current conditions. C) Net change map of habitat suitability under the pessimistic SSP5-8.5 pathway (2040–2050), demonstrating widespread habitat contraction and residual suitability areas.

In the most optimistic scenario (SSP1-1.9), suitable habitat areas were reduced by 89.7%, and Colombia became the country with the highest relative resilience, conserving 14.5% of its original range. In contrast, Costa Rica suffered a total loss of suitable areas, suggesting a sharp local contraction of the species' niche. Panama and Nicaragua retained less than 5% of the habitat area predicted for *E. lucunter*.

In the pessimistic SSP5-8.5 scenario, habitat losses were even more severe, with an overall reduction of up to 98.8%. In this projection, Costa Rica remained in a state similar to the current one, while Nicaragua and Panama lost more than 98% of their potential habitat. Colombia retained 1.9% of its habitable area, equivalent to 131.84 km², mainly associated with island regions.

4. Discussion

Our results confirm that Echinometra lucunter is a species strictly associated with shallow, nearshore benthic environments, consistent with its affinity for rocky substrates and high wave energy (Deucher et al., 2024; Hendler, 1995). This dependency on specific physiographic and topographic conditions defines the species' potential niche under contemporary conditions.

However, when these structural variables remain constant in future projections, marine hydrochemical factors emerge as the main determinants of variation in habitat suitability. Under projected scenarios, changes in temperature, pH, and primary productivity could therefore alter not only the physiological viability of Echinometra lucunter, but also its functional role within reef ecosystems.

In the Mexican Caribbean, trophic models developed by Arias-González (1998) demonstrated that variations in community structure and biomass at higher trophic levels translate into significant changes in energy flow and ecosystem production. In this context, reductions in environmental suitability for herbivo-rous and bioerosion species could trigger comparable trophic reorganizations.

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Empirical evidence from the Eastern Tropical Pacific has demonstrated that echinoid-driven bioerosion exhibits density-dependent thresholds capable of shifting carbonate budgets from net accretion to net erosion, thereby altering the structural trajectory of reef systems (Alvarado et al., 2012). Under climate-induced contractions of suitable habitat, alterations in the abundance of E. lucunter could therefore generate nonlinear responses in reef carbonate balance, amplifying the ecosystem-level consequences of hydrochemical change.

The spatial disparities observed in this study regarding the suitability of con-temporary habitat among all locations studied, reveal that variations in the structure and complexity of the coastal systems can determine whether the loca-tion is more susceptible or less susceptible to climate shifts. Similarly, studies in Colombia and Panama have associated high echinoderm diversity with great-er habitat heterogeneity and marine and coastal ecosystem breadth (Alvarado, 2011),

suggesting that regional structural complexity may modulate the spatial resili-ency of projected environmental suitability.

Additionally and to a smaller extent, suitable areas predicted for Nicaragua and Costa Rica reflect a combination of narrower coastal shelves and lower envi-ronmental complexities, suggest nontheless that variations in projected hydro-chemical conditions is the main factor associated with niche contraction.

In these countries, projected changes in sea surface temperature and pH could significantly reduce the environmental resiliency o suitable areas for E. lu-cunter, limiting the effective availability of suitable habitats despite coastal complexity.

Furthermore, the potential climate niche of E. lucunter, represented in geo-graphical space (G space), differs for each future scenario, as reflected in the low niche overlap values. The results show a clear contraction of the niche in the optimistic SSP1-1.9 scenario, associated with reductions in CO_2 emissions (UN, 2015), indicating that even under mitigation trajectories, a substantial loss of suitable climate space persists. Although regions such as Colombia and Pan-ama retain areas of high suitability, this persistence appears to be related to greater contemporary environmental breadth that could partially buffer project-ed hydrochemical variability (Rodríguez-Ramírez et al., 2010). In contrast, the predicted loss of habitable areas in Nicaragua and Costa Rica suggests that, in contexts where future climate variation exceeds the ranges currently occupied by the species, local populations could experience a marked reduction in their climatic niche.

However, the interpretation of these contractions must consider that Caribbean reefs have undergone substantial changes in their community structure. Studies have shown that many modern reefs lie outside the range defined by pre-human communities of the Middle Holocene (O'Dea et al., 2020), suggesting that cur-rent systems already represent modified ecological states. In this context, the response of functionally relevant species such as E. lucunter could depend on both the magnitude of projected climate variation and the contemporary ecolog-ical state of the reefs.

Under the pessimistic SSP5-8.5 scenario, the potential niche contraction is even more pronounced, with niche overlap values approaching zero. This suggests the emergence of future environmental conditions that are non-analogous to those currently occupied by the species. This pattern may be associated with shifts in key oceanographic variables, such as mean chlorophyll-a, which is linked to primary productivity and, consequently, food availability for E. lucunter. Other variables, such as salinity range and current velocity, also contribute to habitat suitability, albeit with less influence compared to the primary predictors.

pH variability not only indicates an environment characterized by abrupt fluctuations but is also intrinsically linked to the process of ocean acidification that has intensified in recent decades. This phenomenon reduces the bioavailability of calcium carbonate, an essential component for the formation of the calcareous endoskeleton in many marine organisms (Carrillo, 2021; Courtney et al., 2013; Ramos, 2023). Experimental studies have revealed that predicted increases in temperature and ocean acidification over the coming decades could negatively impact the fertility rate of E. lucunter, as well as embryonic and larval development rates; consequently, overall species abundance will be compromised (Caetano et al., 2021; Pereira et al., 2020). Taken together, these potential physiological

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impacts are consistent with the patterns of habitat suitability loss and severe niche contractions predicted in this study.

In this context, areas with a high probability of occurrence are restricted to spe-cific sites in the Caribbean, mainly Colombian localities such as La Guajira and the San Andrés and Providencia archipelago. These areas may represent resili-ent zones under climatic variation, although their role as potential climate refu-gia warrants further evaluation through higher-resolution spatial and physiolog-ical studies.

5. Conclusions

Here we show that a drastic and widespread reduction in suitable habitat for Echinometra lucunter in the Caribbean Sea under future climate change scenar-ios. This contraction is considere even under the laxer SSP1-1.9 scenarios and it is shown to be intensified under other pessimistic scenarios such as SSP5-8.5. Overall losses under such models exceed 98% of the habitable area and poten-tial local extinctions in Costa Rica and Nicaragua are projected.

Environmental variables were analysed and conclude that future distribution of the species will be primarily driven by changes in the chemical conditions of seawater, with pH variability being the most influential predictor for coverage reduction. Additionally, alterations in temperature and primary productivity (chlorophyll-a) contribute to the loss of habitat suitability, compromising the species' physiological and reproductive viability. These results suggest that E. lucunter is highly sensitive to anthropogenic ocean acidification.

Despite this adverse outlook, specific coastal and insular regions of Colombia, such as La Guajira and the San Andrés and Providencia archipelago, may func-tion as relatively resilient zones, likely due to their environmental heterogenei-ty. These regions should be prioritized for spatially explicit conservation strate-gies, ecological monitoring, and adaptive management. Collectively, our find-ings position E. lucunter as a sensitive bioindicator that reveal impacts on shal-low benthic ecosystems in the Caribbean's climatic conditions and underscore the urgency of integrating climate projections into marine conservation plan-ning and alert systems for local fisheries.

Zenodo: (Campo & Díaz., 2026) [https://doi.org/10.5281/zenodo.18210568].

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Conflicts of Interest: The authors declare no conflicts of interest. This manuscript represents original work and has not been previously submitted for publication in any other journal.

Appendix A

Table A1. List of oceanographic variables used to model habitat suitability for *E. lucunter* in the Caribbean Sea.

Variables Oceanograficas	Fuentes
Batimetría media (m)	MARSPEC
Concavidad media (grados)	MARSPEC
Distancia media a la costa (m)	MARSPEC
Rango de temperatura (°C)	BIO-ORACLE
Velocidad media de la corriente (m.s-1)	BIO-ORACLE
Clorofila media (mg . m-3)	BIO-ORACLE
Rango de pH	BIO-ORACLE
Rango de salinidad	BIO-ORACLE

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Table A2. Niche overlap indices; Schoener's D and Bray-Curtis.

		D	BC	
Solapamiento en G-Espacio	Actual vs SSP1-1.9	0.12	0.06	-
	Actual vs SSP5-8.5	0.015	0.007	-
	SSP1-1.9 vs SSP5-8.5	0.14	0.07	-

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