Predicting the present-day distribution of *Elphidium crispum* through species distribution modeling

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Abstract. Benthic foraminifera are widely recognized as sensitive bioindicators of marine environmental conditions, yet their large-scale ecological niches remain poorly quantified. *Elphidium crispum*, a cosmopolitan epifaunal species typical of temperate shelves, plays an important role in benthic ecosystems and paleoenvironmental reconstructions. The research applied a Species Distribution Modeling (SDM) technique with the MaxEnt algorithm to forecast the *E. crispum* habitat suitability worldwide today, georeferenced occurrences and oceanographic variables (temperature, salinity, dissolved oxygen, pH, primary productivity, and bathymetry) being the basis. AUC of 0.989 was excellent predictive performance by the model, and the dominant environmental drivers were identified as primary productivity and temperature, oxygen and bathymetry next. Areas of high suitability predicted mainly run along temperate, productive continental shelves, especially in the North Atlantic, Mediterranean, Northwest Pacific, southern Australia-New Zealand, and some South Atlantic and Pacific margins. Thus, it will be possible to bring out the impact of food and heat on *E. crispum* distribution, and its oxygenated, shelf-linked habitats will be confirmed. The paper presents the first global-scale quantitative evaluation of *E. crispum's* ecological niche which will be a great help in the future for monitoring, biogeographical analysis, and paleoenvironmental interpretations of the ocean condition change. **Keywords**: *Elphidium crispum*, Species Distribution Model (SDM), MaxEnt, habitat suitability, benthic foraminifera

1 Introduction

Benthic foraminifera are unicellular protists that inhabit marine sediments and play a fundamental role in marine ecosystem functioning and monitoring. Their high abundance, rapid turnover, and sensitivity to physicochemical parameters make them excellent indicators of environmental variability and ecological quality [1] . Because they respond quickly to fluctuations in temperature, salinity, pH, oxygen, and organic-matter flux, benthic

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foraminifera have been widely used to assess pollution, eutrophication, and oxygen depletion in coastal and shelf environments [2] .

Within this group, the genus *Elphidium* is among the most widespread in temperate to subpolar marine settings and is commonly associated with productive, oxygenated, and shallow-water environments [3]. *Elphidium crispum* in particular is an epifaunal shelf species that thrives in sandy to silty substrates and tolerates moderate salinity and temperature ranges. Its sensitivity to organic-matter supply, oxygenation, and bottom-water conditions makes it a valuable proxy for reconstructing paleo-productivity and paleoclimate changes [4]. Despite its cosmopolitan occurrence, global quantitative assessments of *E. crispum* ecological niche and environmental limits remain scarce.

In recent decades, Species Distribution Models (SDMs)—and particularly the MaxEnt algorithm—have become powerful tools for predicting potential species ranges from presence-only data and environmental predictors [5]. SDMs have been successfully applied to marine taxa to identify key environmental drivers and map areas of habitat suitability under present and future conditions [6] . However, the global-scale application of these techniques to benthic foraminifera is still very limited. The majority of the past research on Elphidium has been either local or regional—concentrated on Mediterranean or North Atlantic shelves thus leaving a considerable knowledge gap regarding the species' global biogeography as environmental constraints.

In line with this, the current research intends to use MaxEnt and high-resolution marine environmental data to model and delineate the global habitat suitability of *Elphidium crispum*. The study is designed to achieve the following three objectives:

(1) to determine the major environmental factors that affect its distribution;

(2) to create a worldwide map of potential habitat suitability; and

(3) to explain the ecological and biogeographical implications of the predicted patterns.

By quantifying the present-day environmental niche of *E. crispum*, this research provides a baseline for future assessments of climate-driven range shifts, and for improving paleoenvironmental reconstructions based on benthic foraminiferal assemblages.

2 Materials and Methods

2.1 Species-occurrence data

Georeferenced records of the benthic foraminifera *Elphidium crispum* were compiled from global marine biodiversity repositories [7]. Duplicate and land-based points were removed, and records were visually inspected in R v4.x using the packages sf and rnaturalearth.

To reduce spatial sampling bias, occurrences were thinned to one presence per 0.05° grid cell (~5 km × 5 km) using the spThin algorithm. The final dataset contained N = 180 unique presences spanning the temperate and subtropical shelves of the Atlantic, Pacific, and Indian Oceans. Coordinates were stored in comma-separated (CSV) format and projected in WGS-84.

2.2 Environmental variables

Six continuous oceanographic predictors representing present-day benthic conditions were selected from the Bio-ORACLE v3 [8] database and bathymetry:

Table 1. Environmental variables used for modeling the global distribution of *Elphidium crispum*

Variable	Symbol	Units	Source
Temperature	ST	°C	Bio-ORACLE v3 [8]
Salinity	SAL	psu	
Dissolved oxygen	OXY	$\mu mol\ kg^{-1}$	
pH (total scale)	pH	–	
Net primary productivity	NPP	$mg\ C\ m^{-2}\ day^{-1}$	
Bathymetry	DEP	m	

2.3 Species-distribution modeling

Potential habitat suitability was modeled using the maximum entropy algorithm implemented in the maxent function of the R package dismo, equivalent to MaxEnt v3.4 [9].
MaxEnt estimates the probability distribution of maximum entropy for a species' presence under constraints imposed by environmental predictors [10].

Model convergence was reached at 500 iterations. Presence records were split 75 % for training and 25 % for testing.

2.4 Model evaluation and habitat-suitability classification

Model accuracy was quantified by the Area Under the Receiver-Operating-Characteristic Curve (AUC). AUC values between 0.9 and 1 indicate excellent predictive performance[11]. The regularized training gain was also recorded to assess model explanatory power.
Based on logistic suitability, the predicted surface was categorized into four suitability classes:

Table 2. Habitat-suitability classes used to interpret MaxEnt logistic output for Elphidium crispum

Class	Unsuitable	Low suitability	Moderate suitability	High suitability
Range	0–0.1	0.1–0.3	0.3–0.6	0.6–1.0

2.5 Map production

Predicted logistic outputs were exported as GeoTIFF and visualized in QGIS 3.30.2 and R (ggplot2). Suitability was mapped globally with coastlines from rnaturalearth. All analyses were performed in RStudio on a Windows 10 64-bit.

3 Results

3.1 Model performance

The MaxEnt model for *Elphidium crispum* showed excellent discriminatory power. The ROC curve for training data yielded AUC = 0.989, well above random expectation (0.5), indicating highly accurate separation of suitable vs. unsuitable environments[12] (Fig. 1). The omission vs. predicted area curve closely tracked the expected omission at low thresholds and diverged positively at more conservative thresholds, supporting robust model generalization (Fig. 2).

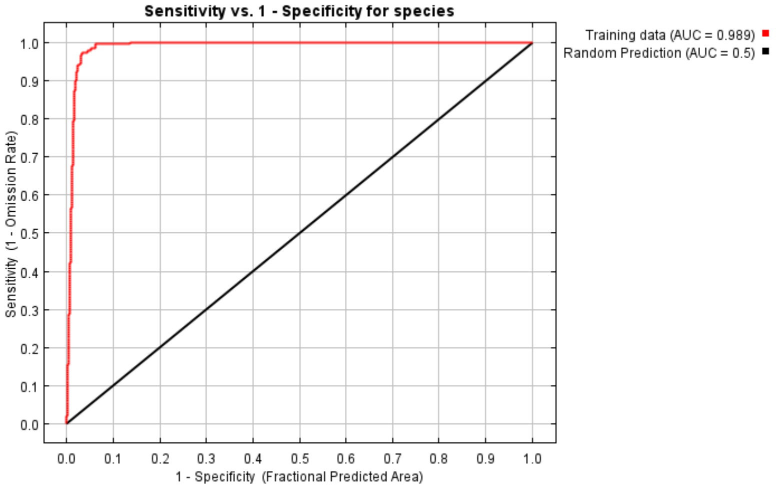

Fig 1. Sensitivity vs. 1–Specificity (AUC = 0.989)

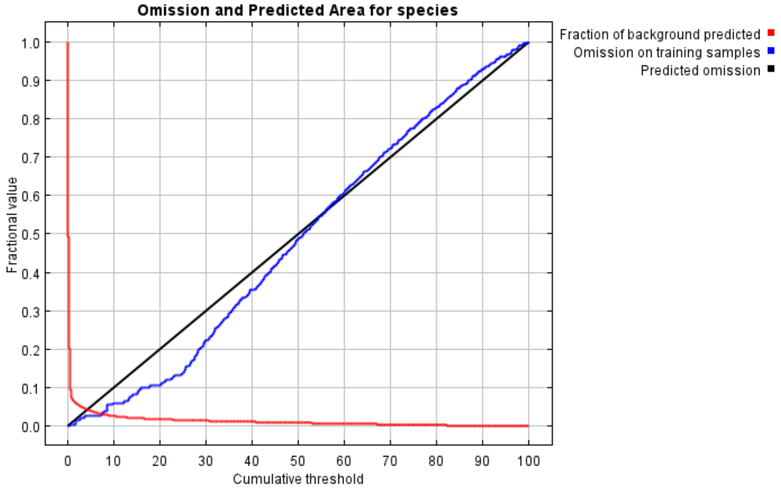

Fig. 2. Omission vs. predicted area.

3.2 Environmental drivers of suitability

The variable importance table and MaxEnt jackknife indicate that suitability is primarily driven by primary productivity and temperature, followed by dissolved oxygen, bathymetry, and weaker effects of salinity and pH (Table 1). Specifically, Percent contribution was: prod 61.1%, temp 24.2%, oxygen 5.8%, bathy 5.0%, salinity 2.5%, pH 1.4%; corresponding Permutation importance: 41.7, 19.0, 17.6, 16.7, 0.4, and 4.6, respectively (Table 3) This pattern aligns with marine SDM literature where scenopoetic climate–ocean variables dominate presence-only models, and where a moderate number of predictors is generally adequate for excellent AUC.

Table 3. Percent contribution and permutation importance of environmental variables

Variable	Percent contribution (%)	Permutation importance (%)
Primary productivity	61.1	41.7
Temperature	24.2	19.0
Dissolved oxygen	5.8	17.6
Bathymetry	5.0	16.7
Salinity	2.5	0.4
pH	1.4	4.6

3.3 Collinearity check and retained predictors

The environmental variable correlation heatmap confirmed high collinearity among several raw layers. We therefore retained the compact set used by the final model. (Fig. 3).

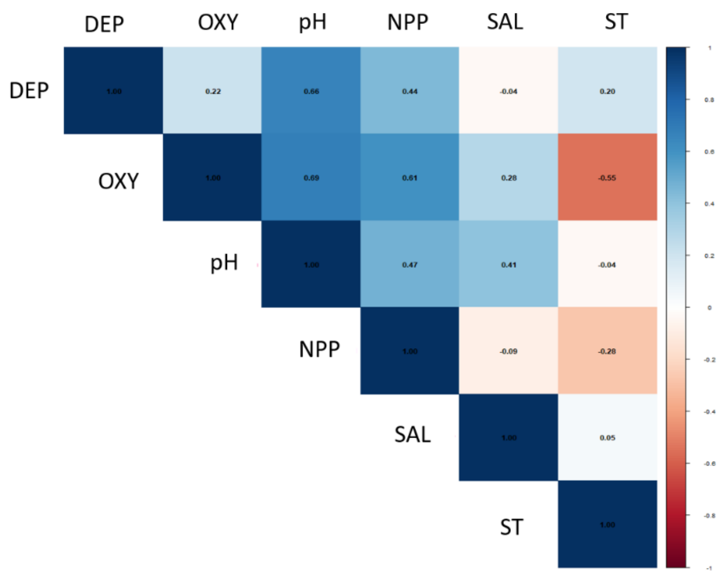

Fig. 3. Correlation heatmap of candidate predictors

3.4 Predicted global habitat suitability

The global suitability map highlights elevated logistic suitability along temperate to warm-temperate continental shelf systems, with higher values tracking productive coastal and upwelling-influenced waters and decreasing toward oligotrophic open-ocean gyres (Fig. 2). Suitability also trends with moderate bathymetric ranges and favorable oxygen–temperature envelopes inferred from response curves.The map indicates coherent biogeographic patterns consistent with the model's leading drivers (primary productivity and temperature).

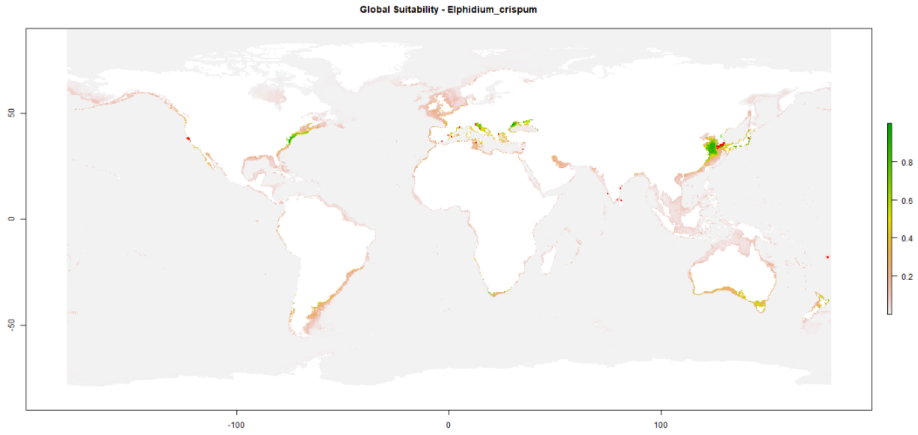

Fig 4. Global suitability for *E. crispum*

4 Interpretation and Discussion

The MaxEnt model for *Elphidium crispum* showed excellent predictive skill (AUC ≈0.989), confirming a robust separation between suitable and unsuitable habitats[10]. Such high performance aligns with previous SDM evaluations where MaxEnt consistently yields strong AUC/TSS metrics across taxa.

Primary productivity (61.1%) and temperature (24.2%) emerged as the dominant drivers of habitat suitability, highlighting the importance of food flux to the seafloor and thermal regime in shaping benthic foraminiferal distributions. This is consistent with long-established ecological models linking organic-matter delivery and temperature to benthic foraminiferal abundance and diversity [13].

Dissolved oxygen also contributed substantially, reflecting its mechanistic role in defining microhabitats and ecological tolerances [14]. Bathymetry reinforced the species' shelf affinity, consistent with the distribution of *Elphidium spp*. in shallow, food-rich marine environments.

Although salinity and pH showed minor global influence, experimental evidence indicates strong local effects on calcification and survival [15]. These variables may become more critical under ongoing ocean-acidification and deoxygenation trends.

Spatially, high suitability concentrated on temperate, productive continental shelves—notably the NE/NW Atlantic, Mediterranean, NW Pacific, and southern Australia–New Zealand—mirroring observed *Elphidium* occurrences in modern faunas. Such areas combine favorable productivity, moderate temperature, and oxygenation conditions, validating the ecological realism of the model.

Overall, the results depict *E. crispum* as a temperate, food-limited, shelf-associated epifaunal species, whose distribution is primarily constrained by productivity and thermal–oxygen dynamics. The model provides a baseline for identifying sampling priorities and for projecting future range responses under warming, deoxygenation, and acidification.

5 Conclusion

The study utilized the MaxEnt algorithm to model the global habitat suitability for *Elphidium crispum* and it achieved an impressive predictive performance (AUC ≈ 0.989). The environmental factors that had the greatest influence on the species were identified as the primary productivity and temperature, while the other factors such as dissolved oxygen and bathymetry came next in line. This confirmed that *E. crispum* is a species that prefers temperate, productive, and well-oxygenated continental shelf areas. The analysis not only provided a better insight into the ecology and biogeography of *E. crispum* but also laid down a definite foundation for monitoring environmental change and improving the paleoenvironmental reconstructions based on forams. Besides, the model can be used as a reference point for the assessment of species distribution shifts in the coming ocean temperature rise, deoxygenation, and acidification scenarios. Taking everything into consideration, this research has provided the first assessment of *E. crispum* habitat suitability on a global scale and at the same time has indicated the major oceanographic factors that are influencing the distribution of this species now and in the future.

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