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MODELLING THE SPATIAL DISTRIBUTION OF THREE RED SEA SPECIES IN THE GREEK SEAS

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Abstract

Red Sea species have entered the Mediterranean Sea since the opening of the Suez Canal. As they rapidly establish local populations and increase their abundance they form a potential threat for local biodiversity and fisheries. Here, we focus on three invasive alien, demersal fish species, *Pterois miles*, *Siganus luridus* and *Siganus rivulatus*. Georeferenced records from online databases, published scientific literature and questionnaires were assembled within a Species Distribution Modelling approach aiming to map the suitable habitat of the target species over the Greek Seas. Using the Maximum Entropy modelling approach, we constructed a habitat suitability model correlating species occurrence data from the Eastern Mediterranean basin with environmental and topographic explanatory variables. Results highlight the strong coastal nature of all three species and their association with the presence of *Posidonia oceanica* meadows. Probability maps were constructed based on the selected models for the wider Greek Seas area, evidencing high presence probabilities mainly in southeastern coasts and the Ionian Sea for all the species, and a probable expansion everywhere in the study area with the exception of the Thracian Sea for *P. miles* and *S. luridus*, as this sea currently seems to exhibit unfavorable to the species environmental conditions.

Keywords: maximum entropy, habitat suitability, alien species, invasive, marine.

1. Introduction

Introductions of non-indigenous species have been considered a major driver of change in the Mediterranean Sea (Golani, 1998) and the majority consists of thermophilic Red Sea species introduced through the Suez Canal (Karachle *et al.*, 2018). Here, we focus on three demersal fish species, the venomous *Siganus luridus* (Rüppell, 1829) (dusky spinefoot), *Siganus rivulatus* (Forsskål & Niebuhr, 1775) (marbled spinefoot) and *Pterois miles* (Bennett, 1828) (lionfish). All three species have succeeded in establishing populations and expanding their distribution throughout the eastern Mediterranean. *P. miles* although native to the Indian Ocean, has established a population in the Mediterranean in the last decade (Dimitriadis *et al.*, 2020). Both *S. luridus* and *S. rivulatus* are originally distributed in the Western Indian Ocean and count more than fifty years of occurrence in the eastern Mediterranean (Golani, 1998). All three species are edible and seem to slowly enter the commercial fisheries in Greece. In the current work, we aim to assess the potential spatial distribution of the three species over the entire Greek Seas using Species Distribution Modelling quantifying the distribution of the species along environmental gradients. Subsequently, the selected models were used for forecasting and assessing habitat maps to indicate those geographic areas where environmental variables, in the absence of explicit biotic interactions (such as competition or predation), are considered suitable for the presence of the particular species.

2. Material and Methods

A spatial dataset on species occurrences was constructed based on georeferenced observations along the Eastern Mediterranean coastal waters, dating from 2010 to present, originated by various sources of information: databases (i.e., offline ELNAIS database, Zenetos *et al.*, 2015; www.gbif.org), published scientific literature and questionnaires filled by local fishers (Margaritis *et al.*, 2021). Data were filtered

using the spThin R package (Aiello-Lammens *et al.*, 2015) to retain the highest number of records being at least 9km apart in order to condense any spatial autocorrelation issues in modelling. Subsequently, Species Distribution Modelling (SDM) was applied to georeferenced information of species' presence to quantify the distribution of the species along physical and environmental gradients. Satellite environmental data were used as explanatory variables to model the suitable habitat of the target species. Sea surface temperature (SST in ^{o}C; oceancolor.gsfc.nasa.gov) of the warmest month, SST of the coldest month, SST range, sea surface salinity (SSS in psu; marine.copernicus.eu) of the least saline month and sea surface chlorophyll (CHL in mg/m^3; oceancolor.gsfc.nasa.gov) of the most productive month were downloaded from the respective databases for the period 2010-2020 and used in SDM. These environmental variables are considered important either as a direct influence on the distribution of fish (e.g., SST, CHL) or as proxies for causal factors. Bottom depth was derived from the GEBCO portal (General Bathymetric Chart of the Oceans GEBCO_2021 Grid, DEP in m; www.gebco.net) along with, bottom slope. Finally, a model-based quantification of *Posidonia oceanica* meadows was downloaded from the EMODNET portal (https://emodnet.ec.europa.eu/en). All monthly-averaged satellite images from daily measurements were processed as regular grids at a spatial resolution of 400 x 400 m^2 under a GIS (Geographic Information Systems) environment using ArcInfo GRID software.

Maximum Entropy, an SDM approach (Phillips *et al.*, 2017) specialized for modeling species distributions from presence-only records, was subsequently applied using the MaxEnt ver. 3.4.4 software (Phillips *et al.*, 2017). Models were trained using pooled data from the wider Eastern Mediterranean Sea, while background points for modeling were selected solely within the current confirmed boundaries of the distribution of each species. A 5-fold cross-validation method was selected and the accuracy of the models was evaluated using the Receiver Operating Characteristic curve and the Area Under Curve (AUC) metric along with True Skill Statistics (TSS). Finally, the predictor importance was evaluated with jackknife analysis and a logistic output was selected because of its extensive use in bibliography and ease in interpretation. In order to examine the possibility of extrapolation beyond training conditions, we used MESS analysis (Multivariate Environmental Similarity Surface) and produced the corresponding maps.

3. Results

The most important variable was bottom depth for all species, followed by the presence of *P. oceanica* meadows. On the contrary, annual SST range contributed the least to the models for all species. SSS of the least saline month had very small contribution on *Siganus* species' models but was moderately important for *P. miles*. SST of the coldest month and bottom slope seem to have low to moderate contribution to all models, while SST of the warmest month play a limited role for *P. miles* but was more important for the two *Siganus* species. Chlorophyll of the most productive month is more or less equally important to all species with higher probabilities of presence within 0.20 – 2.5 mg/m^3, besides *S. rivulatus* which exhibits high probabilities of occurrence in higher chlorophyll concentrations too. MaxEnt map predictions for all three species are depicted in Figure 1, along with jackknife analyses tables. Maps produced confirmed the known extended presence of *P. miles* in the southern part of the Greek Seas (i.e., Crete, Cyclades, Dodecanese), the coastal part of the eastern Ionian Sea and the Gulf of Patras. The species seems to be able to expand its suitable habitat as north as the Chalkidiki peninsula and Limnos island in the North Aegean. Areas with a low probability of presence of *P. miles* include North Evoikos Gulf, Korinthiakos Gulf and the Thracian Sea. Respective maps were very similar for *S. luridus*, while *S. rivulatus* exhibits relatively higher probabilities of presence in the Thracian Sea. According to MESS analysis, the values of the environmental variables fall outside the range of the training conditions in the Thracian Sea and partially at Thermaikos Gulf, as indicated by the negative values of the analysis in the above areas. Consequently, we should be particularly cautious with interpretations in the aforementioned areas. Prediction accuracy proved to be high as AUC was >0.92 for all species, and the threshold-dependent metric of TSS scored satisfactory high values as well (>0.76 for all species).

4. Discussion

Areas favoring the occurrence of all three species the most consist of shallow waters with high probability of *P. oceanica* meadows presence. Specifically, all three species exhibit high probabilities of pres-

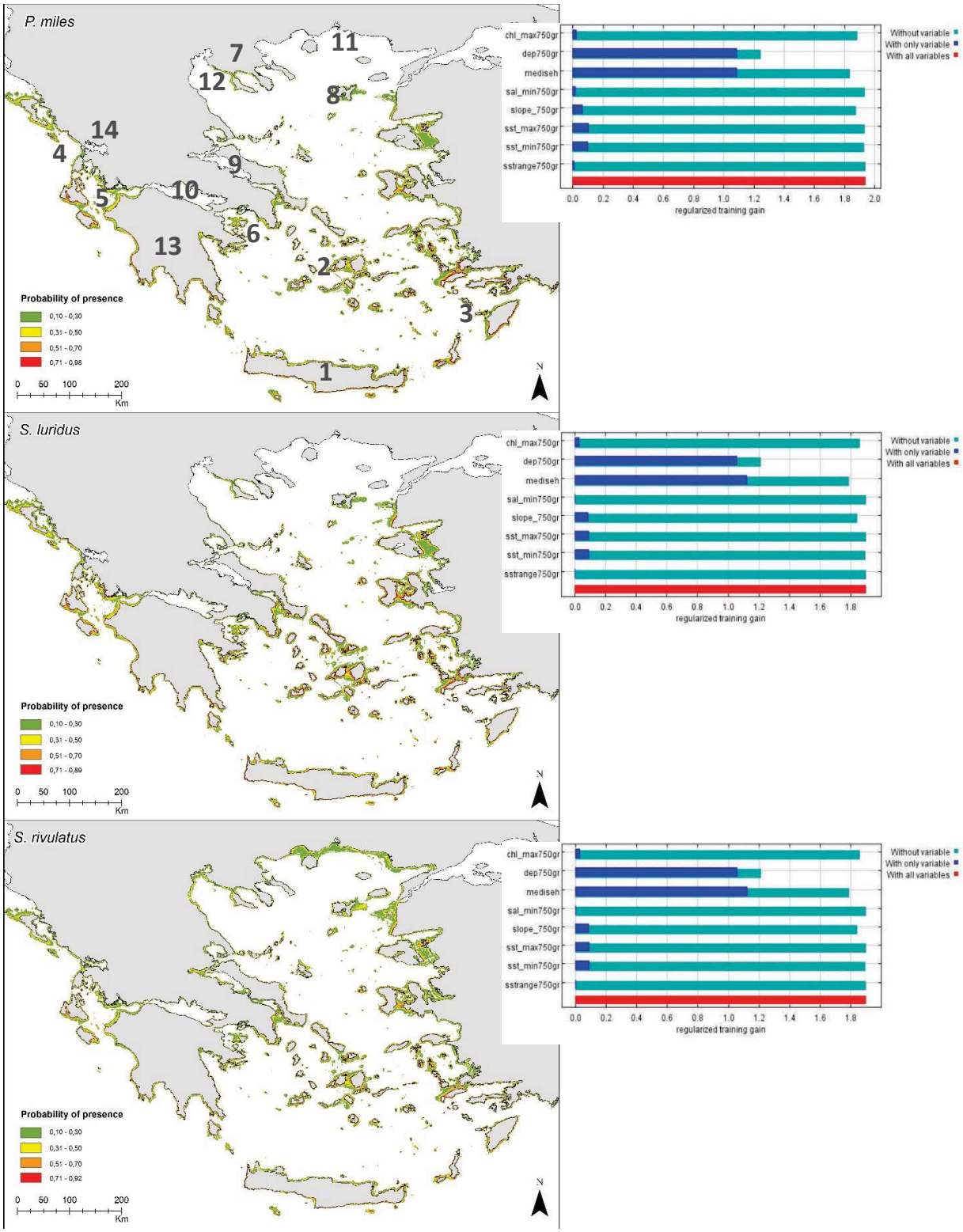

Fig. 1: Probability of occurrence, ranging from 0 to 1, for P. miles, S. luridus and S. rivulatus in the Greek Seas as predicted by maximum entropy modeling approach and the corresponding jackknife analysis tables. Probabilities lower than 0.1 are not depicted on the maps. 1 Crete; 2 Cyclades; 3 Dodecanese; 4 Ionian Sea; 5 Gulf of Patras; 6 Argosaronikos Gulf; 7 Chalkidiki; 8 Limnos; 9 North Evoikos Gulf; 10 Korinthiakos Gulf; 11 Thracian Sea; 12 Thermaikos Gulf; 13 Peloponnese; 14 Amvrakikos Gulf.

ence (>50%) in depths ranging from 0 to approximately 40 m when combined with *P. oceanica* meadows. Both *Siganus* species are herbivorous, feeding on the epiphytes associated to phanerogams and to a lesser extent on the phanerogams (e.g., Stergiou, 1988 and references therein), while *P. miles* is likely to feed on the fish and crustacean species associated with the meadows (e.g., Zannaki *et al*., 2019). Furthermore, *P. miles'* probability of presence increases with the increase in SSS of the least saline month, an outcome anticipated by the fact that most records are found in the southern parts of Greek waters, where saline waters with very limited freshwater inflows occur. The low contribution of SST of the warmest month to the selected model of *P. miles* was an outcome much expected by its tropical origin. SST temperatures of the warmest month do not seem to restrict the species' expansion. On the contrary, *S. luridus* and *S. rivulatus* are affected by SST of the warmest month reaching their higher probability of occurrence between 26 and 28 °C. Regarding SST of the coldest month, *P. miles* has higher probabilities of presence close to 17 °C, while *S. luridus* and *S. rivulatus* exhibit their peaks at colder waters, close to 14 °C. As alien species usually shift their niche when located away from their native range (D' Amen & Azzurro, 2020) this makes the prediction of their future expansion a challenging procedure. Our results predict the probable expansion of the three species over the largest part of the Greek Seas, especially for *S. rivulatus*. Dimitriadis *et al*. (2020) predictions for *P. miles* are quite similar to current findings, opposed to Poursanidis *et al.* (2020) and D'Amen & Azzurro (2020), who limit the expansion of the species in the southeastern coasts of Greece.

Modelling approaches could probably be enhanced by the inclusion of variables arising from biotic interactions between alien and native species. For example, predation rates, interspecific competition and feeding habits could, among other factors, explain the rapid expansion and spatial distribution of some alien species in the Mediterranean (e.g., Azzurro *et al.*, 2007; Ulman *et al.*, 2021).

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