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Uncertainty in Marine Species Distribution Modelling: Trying to Locate Invasion Hotspots for *Pterois miles* in the Eastern Mediterranean Sea

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Abstract: Biological invasions are considered among the largest threats to native biodiversity. The Mediterranean Sea, connecting the Indo-Pacific and Atlantic oceans, is characterized as a global marine invasion hotspot, due to a multitude of human pathways and vectors such as shipping, aquaculture, tourism, and the opening of the Suez Canal, which have led to the introduction of nearly 700 alien species into the Mediterranean Sea. Among the species introduced, the lionfish *Pterois miles* could be considered the fastest spreading invasive fish species of the last decade (2012–2022) and has been recorded in all countries of the eastern Mediterranean Sea, reaching as far north as Croatia. Here, we present a Bayesian additive regression tree modelling framework for an updated species distribution modelling invasion map under current and future climate conditions. All climate uncertainty sources have been used, as these are available from the Bio-Oracle, the unique marine predictors database. Important outputs of the current approach are the model's inadequacy to accurately predict the most recent expansion of species in the Adriatic Sea, and the uncertainty estimation, that are high in areas with confirmed occurrence of individuals, in simulations that can help the decision makers and policy officers understand model limitations and take more informed actions.

Keywords: Bayesian additive regression trees; climate-change; lionfish; Mediterranean Sea; uncertainty estimation

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1. Introduction

Alien species, aided by human agencies, managed to overcome physical barriers and colonize new regions beyond their natural range [1,2]. Every year, new species move and establish populations that can become problematic for native species and habitats, causing severe economic impacts [3,4], due to fast adaptation and the absence of predators that control the population [5] in their native distribution range. On the other hand, the inclusion of the species in the local cuisine due to the plentiful availability as a food source could act as a mitigation action of population control [6]. Both lionfish species,

Pterois miles (Linnaeus, 1758) and *Pterois volitans* (Bennett, 1828), have shown adaptability to quickly establish populations in new environments as revealed by populations in the Mediterranean and the Caribbean Sea. Lionfish are native to the Pacific and Indian Ocean, respectively [7]. During the last three decades, the *Pterois* complex has displayed one of the most disruptive marine biological invasions worldwide [8,9], rapidly spreading throughout the tropical and subtropical coasts of the western Atlantic, the Gulf of Mexico and the Caribbean Sea [10–12].

This unprecedented invasion extended across a wide range of natural habitats [13–15], severely impacting coastal biodiversity as well as ecosystem processes and functions [3,16,17]. Recently, a new lionfish invasion has begun in the Mediterranean Sea. This invasion started in 2012, when two individuals of the common lionfish *P. miles* were recorded from the Lebanese coasts [18]. Since then, the population of *P. miles* has rapidly increased and spread westwards, reaching Sicily and Tunisia [19–21]. Molecular analyses revealed that the invading *P. miles* population is of Red Sea origin founded by individuals immigrating through the Suez Canal [22] in multiple introductions [23]. There are serious concerns about the potential ecological impact of this incipient invasion, since the Mediterranean Sea is a biodiversity hotspot and the world's most invaded marine region [24,25].

Predicting *P. miles*' potential geographic distribution in the Mediterranean Sea under current and future environmental conditions, based on the Intergovernmental Panel on Climate Change (IPCC) climate change scenarios, is among the most urgent research objectives, with concrete applications in conservation, early warning, and invasive-species management. Climate change is expected to further change the geographical distribution of non-indigenous species [26]. Alien species are generally considered to be more likely to cope with climate change allowing them to expand into new regions, as they are generalists with broader climate tolerance [27]. Although there is limited evidence of the current impact of climate change on the distribution of alien species, it is often suggested that climate change is one of the major contributors to future competition [28,29]. The rate of tropical alien species immigration from the Red Sea to the Mediterranean Sea correlates with gradual but steady changes in climatic variables in the Mediterranean region [30]. As parameters of the Mediterranean waters become more similar to those of the Red Sea, aquatic species with analogous physiological response are now able to cross the Suez Canal, which previously acted as a natural barrier, and inhabit the eastern Mediterranean basin [1,31]. The rate of spread of some NIS of Red Sea origin (i.e., *Fistularia commersonni*; 489 km year^{-1}) is significantly higher than from natives (Hiddink et al., 2012) or other biological characteristics [32].

The current work uses a Bayesian framework for the distribution modelling of the lionfish *P. miles* in the Mediterranean Sea under current and future marine climate conditions, expanding the previous work by Poursanidis et al. [33] and provides uncertainty in the predictions as a spatial explicit information, usefully to be incorporated in the process of decision making for targeted activities and robust decisions [1]. The use of uncertainty during modelling processes, where the results will be incorporated in decision making process, is an important step towards clear and informative science for the stakeholders [34].

2. Materials and Methods

Several modelling approaches are available [35], depending on the environmental questions and available data. Here we modelled the realized climatic niche of the taxon under study by combining the available occurrence data with current environmental predictors with 'embarcadero' [36] R package. We used Bayesian additive regression trees (BARTs) and functions from the 'embarcadero' R package. BARTs are a classification tree method defined by a prior distribution and a likelihood for returning occurrence predictions that enables the quantification of uncertainty around the predictions and the estimation of the marginal effects of the covariates [37].

We thereafter generated presence/absence datasets following available recommendations from other studies [38,39] for the taxon under study. We evaluated our model's

performance based on seven metrics [AUC, Sorensen's index, TSS, Brier score, Cohen's kappa, Continuous Boyce Index (CBI), Somer's D] [40–45] and we used a repeated split-sampling approach to evaluate our models [46]. The metrics estimation used was done using functions from the following R packages: 'CalibratR' 0.1.2, 'DescTools' 0.99.40, 'ecospat' 3.2, 'enmSdm' 0.5.3.2, 'Metrics' 0.1.4, 'MLmetrics' 1.1.1 and 'modEvA' 2.0 [47–52]. We reconstructed the potential suitable area of *P. miles* under current and future climate conditions, using the 'predict2.bart' function, excluding any predictors that were not included in our fine-tuned model. Finally, the importance of each variable retained in our final model was estimated using the 'varimp' function of the 'embarcadero' R package.

The environmental data are based on oceanographic variables from the Bio-Oracle database v.2.1 [53] at 8 km pixel size. From the available dataset we used data that already used by D'Amen on Mediterranean Invasive Species and projections [54]. These are pH, salinity (mean and range), sea surface temperature (mean and range), and mean primary productivity. For the climate change predictions, we used the period 2040–2050 with the RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The RCP2.6, a peak-and-decline scenario ending on very low greenhouse gas concentration levels by the end of the 21st century, the RCP4.5 and RCP6.0 where concentration levels stabilize, and the RCP8.5, a scenario of increasing emissions over time leading to high concentration levels of greenhouse gases. The occurrence data used were derived from both the native and invaded area, following the approach in [33] (see Figure S1 in the publication); these were derived from the available literature data [55], the latest GBIF data [56], along with data from the archive of iSea, a Greek Environmental Organization (personal communication).

3. Results and Discussion

Species distribution modelling using Bayesian additive regression trees has been used to identify the potential distribution of *P. miles* in the Mediterranean Sea, along with a prediction for the period 2040–2050 under four RCPs (RCP26, RCP45, RCP60 and RCP85). For the current timeframe, we find the potential distribution area to be limited to areas already known in the eastern Mediterranean Sea, with very few medium value spots of potential occurrence in South Sicily and in Algeria. No further expansion is predicted in the western and northern Mediterranean Sea, or the Adriatic. This contradicts the recent sighting of a juvenile *P. miles* individual (13 cm) in the central Adriatic Sea, in Viz Island [57] and references therein for lionfish sightings in the southern Adriatic Sea. Our simulations predict that the Adriatic Sea is unfavorable for the establishment of a sustainable population under current and projected climate conditions.

The model statistics regarding the accuracy based on multiple metrics is summarized in Table 1 and shows that it has excellent performance across all calculated indices. The performance of our model was exceptionally good, as evidenced by the very low Brier score, i.e., a proper classification metric that is unaffected by prevalence [58]. From the metrics of the model evaluation (Table 1), the model with high accuracy results was the one based on the Boyce index, i.e., a preferred method for the validation of continuous prediction layers, but also the TSS statistic, i.e., which requires the binarization of the continuous layer into a yes/no approach following thresholds that are defined by the coefficients of the model.

The outputs for each period from the current environmental data to the IPCC RCP climate change scenario and its uncertainty estimation is provided in Figures 1–5. Prediction uncertainty was generally low (Figure 6); however, certain areas in the Mediterranean Sea show high uncertainty. These areas are:

i. the Patraikos Gulf, Greece
ii. the Saronikos Gulf extending to the Northern Cyclades, Greece
iii. the area surrounding Chios and Skyros islands, Greece
iv. the area surrounding Corfu Island, Greece
v. South of Sicily, Italy
vi. the Gulf of Lion, France and
vii. Certain scattered areas along the North African coast.

Table 1. Accuracy metrics and indices for the Species Distribution Model of *Pterois miles* in the Mediterranean Sea.

Metric	Value
TSS	0.98
AUC	0.99
Kappa	0.94
Boyce	0.97
Sorensen's index	0.75
Nagelkerke	0.94
McFadden	0.89
Brier	0.008
bias	−0.0004
MAE	0.04
RMSE	0.11
ECE	0.02
MCE	0.01

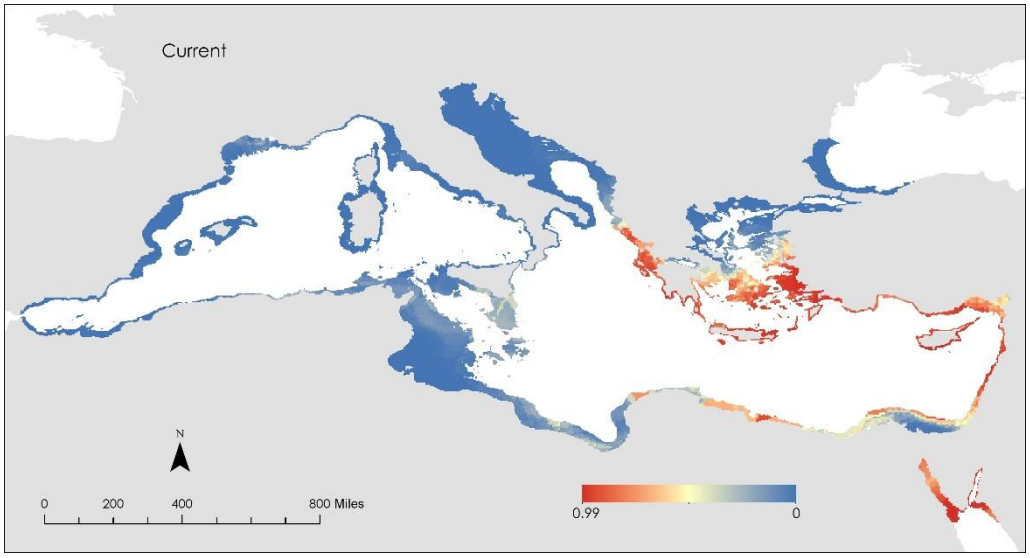

Figure 1. Lionfish potential distribution under current conditions (2000–2014).

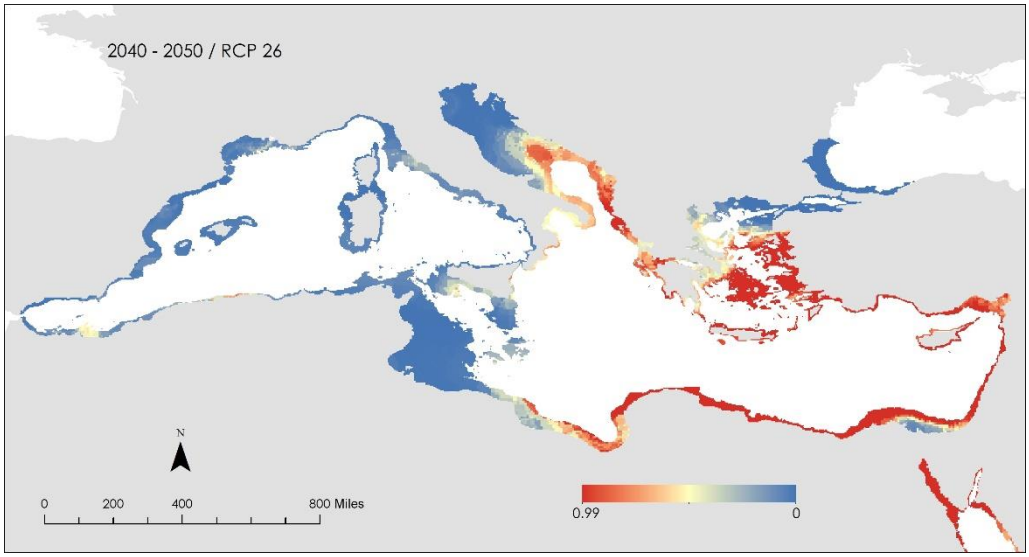

Figure 2. Lionfish potential distribution under RCP26 for the period 2040–2050.

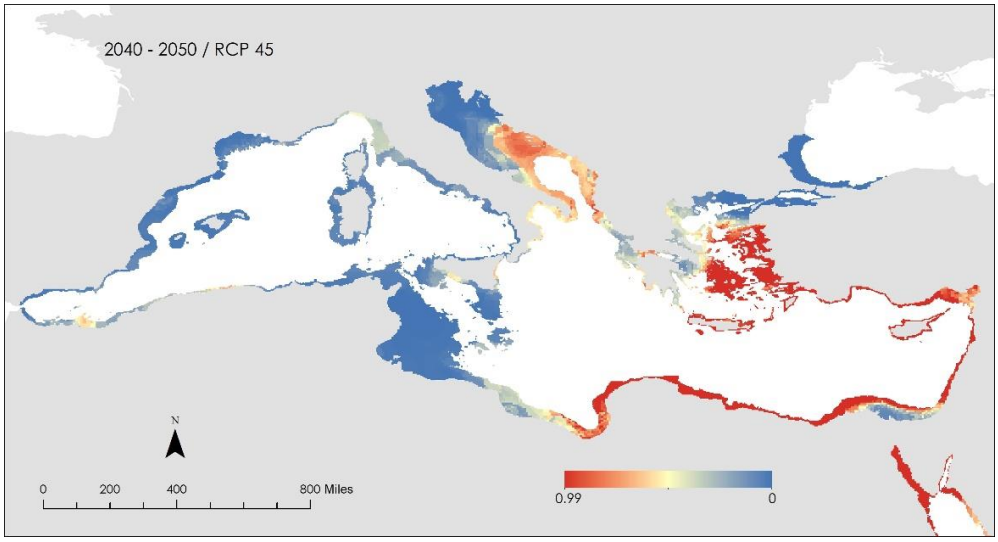

Figure 3. Lionfish potential distribution under RCP45 for the period 2040–2050.

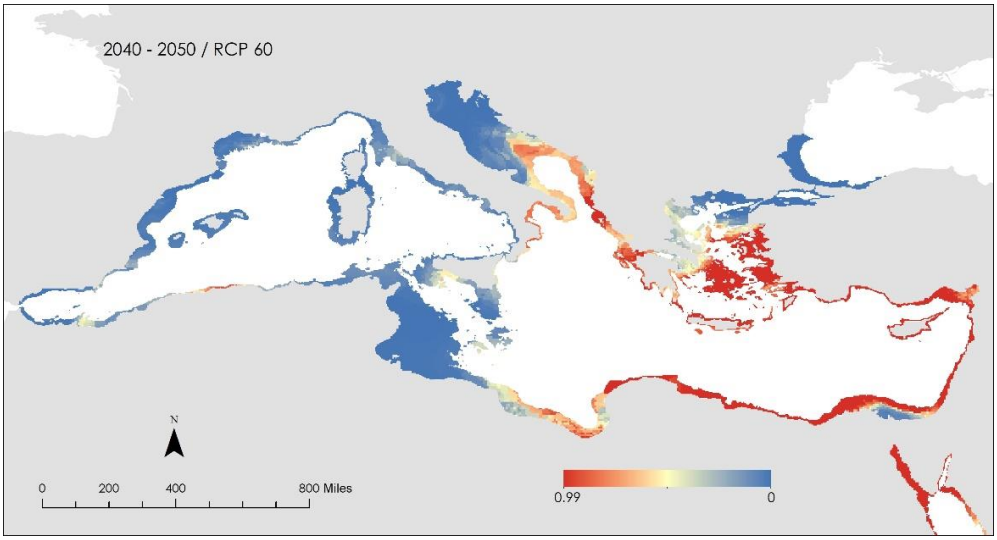

Figure 4. Lionfish potential distribution under RCP60 for the period 2040–2050.

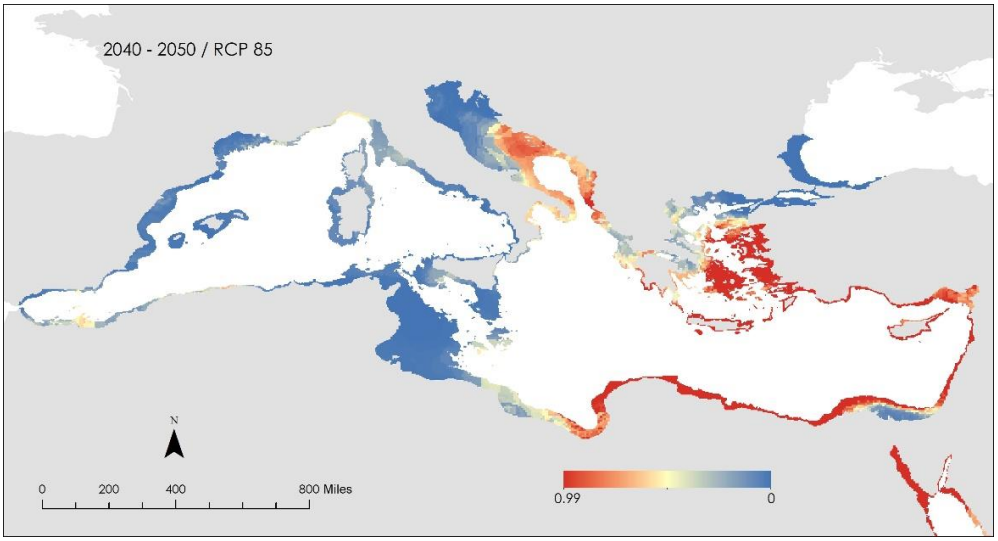

Figure 5. Lionfish potential distribution under RCP85 for the period 2040–2050.

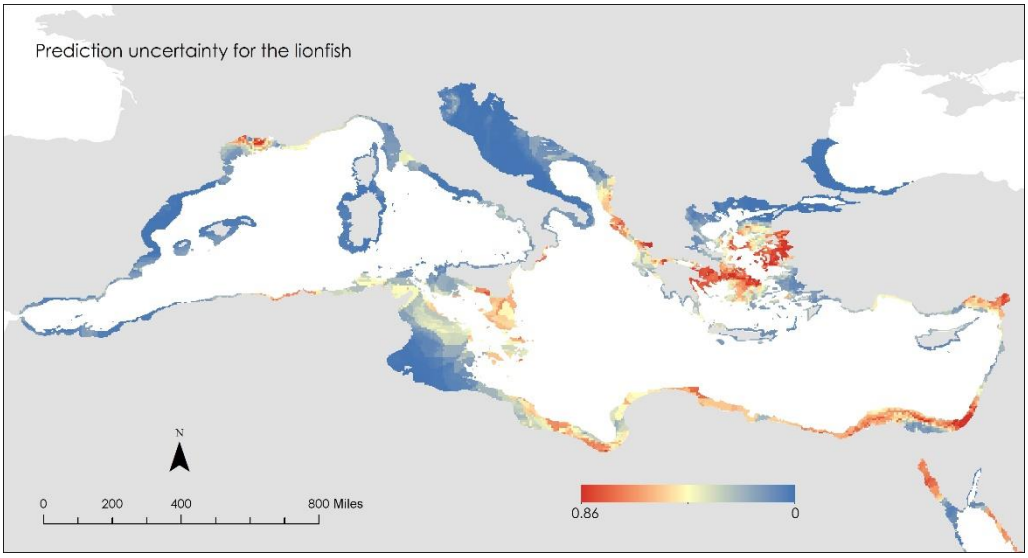

Figure 6. Lionfish prediction uncertainty.

Prediction uncertainty was also high in the Suez Canal, and this is probably attributed to the very high effect of salinity on habitat suitability of *P. miles*. The latter was dealt by setting to zero any cells with high uncertainty values (i.e., with uncertainty values equal to or higher than the 90% uncertainty). Future projections of *P. miles* in the Mediterranean Basin revealed absence from the Ionian Sea (from south of Corfu to the NW coasts of Peloponnese), as well as from areas off the coasts of southern Peloponnese and Kythera. The range expansion of *P. miles* in the Mediterranean Basin is expected in the following areas:

i. The area around Lemnos Island, Greece
ii. The area around the Nile Delta, Egypt
iii. The area around Benghazi, Libya
iv. The area around Algeria

The results from the climate change scenario model gave interesting insights for the Mediterranean Sea. Under the RCP26 and the other RCPs for the timeframe from 2040 to 2050 we produced projection to selected areas in the Adriatic Sea, mostly in the southern parts of it, where records of the species are already available [57], but also for the north-west Africa, Morocco and Algeria and the Gulf of Genoa. We find that salinity plays important role for the distribution of species and the climate change scenarios, a finding that also other studies have concluded [33,57].

Any prediction based on the current available data has to be used and interpreted with caution since all data are based on the IPCC report of 2014. Recently, the new Climate Change Report of 2021, the Physical Science has been released [58], along with the Climate Change 2022: Impacts, Adaptation and Vulnerability [59] (IPCC, 2022). It introduces the new Shared Socioeconomic Pathways (SSPs), which include breakthrough improvements in the projections and the way they introduce how broad socioeconomic trends could shape future society. These are intended to span the range of plausible futures. They include: a world of sustainability-focused growth and equality (SSP1); a "middle of the road" world where trends broadly follow their historical patterns (SSP2); a fragmented world of "resurgent nationalism" (SSP3); a world of ever-increasing inequality (SSP4); and a world of rapid and unconstrained growth in economic output and energy use (SSP5) [60].

However, for the needs of the current work, the available environmental data include climate change scenarios under the Representative Concentration Pathway (RCP); a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. Four pathways were used for climate modeling and research for the IPCC fifth Assessment Report (AR5) in 2014. The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come.

Figures 1–5 provide the results of the model under current climate and future climate scenarios as described above. Sharp changes are observed in the South Adriatic Sea, Central Mediterranean Sea in the straits of Sicily and in some scattered areas in the coastal zone of Morocco/Algeria. However, the uncertainty of the model as it is provided by Figure 6, for the current distribution of the lionfish, provide further insight into the model robustness. Uncertainty is a dimensionless value, an information that provide to the end user how certain is the model at a given area, how confident information is provided and by that how much trustiness can laid to this information. Low values, close to zero, shows that the results are robust, and the end user can trust them for further planning in conservation, removal, designation, spatial planning etc. In the opposite direction, high values shows that the model was not able to understand the conditions that, in our case, the lionfish will face during the spatial expansion and says that even if predictions shows that it might be there, further information on survival, reproduction and establishment of viable populations with large numbers of individuals are not secured. For example, even if we have records from South Sicily or even quite recent from Vis Island in Croatia Sea, no further insights on the population status, the expansion of them and the density are available, showing that these populations might not be able to reproduce due to low temperatures during the winter period in combination with other oceanographic and biological factors.

The used data came from a unique database of marine environmental predictors, well designed, and prepared in analytical workflows for Species Distribution Modelling. The dataset has been prepared followed a standardized approach to deliver SDM-ready data for use by the scientific community for species and ecosystem modelling. However, the update of them using new models and algorithms along with the utilization of the full archive of any available observations from satellites to in situ monitoring systems is lacking behind. Uncertainty is introduced in our study from the definition of the "current" period which is up to 2014; the lionfish invasion appears to start in 2012 and the climax of spread has been reached until 2020. The environmental data does not sufficiently cover this timeframe, in which changes in oceanographic characteristics, such as temperature raise and marine heatwaves along with salinification of the Levantine basin which often coincides with a freshening of the western Ionian Sea [61,62], are not included either in the environmental data nor in the RCP layers. Further, with the publication of the new IPCC report [60], RCPs have been substituted by the SSPs, the Shared Socioeconomic Pathways. No dataset that is "camera-ready" for use in Species Distribution Modelling has made substantial updates to cover the "real" current oceanographic characteristics nor the inclusion of SSPs instead of the previous used RCPs. It is expected that such improvements will substantially improve the modelling activities for Invasive Alien Species, allowing for more robust results and actual use of the information in targeted activities in the domain of conservation, spatial planning, and confrontation.

The designation of a platform where, frequently or after a user's request, environmental predictors will be calculated and prepared for use in environmental modelling will become an important asset and ally towards tackling environmental and societal issues like the Invasive Alien Species. By that, improvement of the current knowledge and more robust projections with their uncertainties will create high quality data to be used in modelling and the process of transparent decision making for management of environmental problems [63,64]. Uncertainty in Species Distribution Modelling is among the priorities for the systematic incorporation into new workflows aimed at support in decision making [65]. However, due to the complexity of the Bayesian frameworks that can provide this important information along with the misinterpretation of uncertainty information and lack of experience in interpreting that into the conceptual understanding of decision makers, it is rarely used in invasive alien species modelling.

The current work uses an updated and modern approach to quantify and map the potential distribution of the lionfish in the Mediterranean Sea using standardized environmental data in a Bayesian modelling framework that allows the calculation of the uncertainty. This information can support targeted activities and informative decisions

incorporating risks. Decision-makers with experience in the use of such information can benefit in the planning of targeted activities by estimating the costs and probability of success balanced between high probabilities and low uncertainties and vice versa. It is expected in the next decade that such approaches will become a standard workflow in species distribution models, from where the results will have a practical use in conservation and planning for the protection or eradication of invasive alien species.

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