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MODELLING CURRENT AND FUTURE DISTRIBUTION OF THE INVASIVE SILVER-CHEEKED TOADFISH *LAGOCEPHALUS SCELERATUS* IN THE MEDITERRANEAN SEA

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ABSTRACT: The progress in species distribution modeling has brought new insights into biological invasion management. The present study aims to model the potential current geographic distribution and future expansion of silver-cheeked toadfish *Lagocephalus sceleratus* in the Mediterranean Sea. Coordinates of 98 occurrence records of *L. sceleratus* in the Mediterranean were used, and marine climatic variables were collected from the global databases. Fifteen modeling techniques were tested, and weighted ensemble averaging of the model replicates was built. AUC values for each model ranged from 0.61 for rpart to 0.99 for rf, and TSS values varied from 0.41 for mlp to 0.95 for rf. Based on the cutoff values of TSS and AUC, the seven modelling algorithms were used for ensemble modeling. The maximum seawater temperature at minimum depth explained strong biological importance to the current adaptation, and the salinity contributed the most to the future adaptation. The ensemble forecasting of suitable habitats of *L. sceleratus* for current distribution modeling revealed that *L. sceleratus* dominantly occurred in the middle and eastern parts of coastal areas of the Mediterranean. The future distribution was extended to the western part of coastal areas of the Mediterranean, classifying the high suitability of these areas for its future distribution. The suitable bioclimatic envelope of *L. sceleratus* under the present study is predicted to widen because of climate change. The likely regions of invasion and the areas at risk for a potential future invasion of *L. sceleratus* indicate that prompt, effective practical actions by resource managers should be undertaken to mitigate its impacts and spread.

KEYWORDS: *Lagocephalus sceleratus*; pufferfish; climate change; species distribution modellings; current and future distribution

INTRODUCTION

Forecasting the present and future geographical range and ecological niche of marine species has increasingly been used by both governments and non-governmental organizations for conservation, assessing and monitoring biodiversity, ecosystem restoration, and ext. (Robertson *et al.* 2010; Marcer *et al.* 2012). Therefore, species distribution models (SDMs) are applied to forecast a species' geographic and environmental range, integrating both spatial and temporal variability.

Knowing the current and predicting the future distribution patterns of alien species richness are becoming crucial for conserving regional biodiversity (Villero *et al.* 2017; Latombe *et al.* 2017; Coro *et al.* 2018; Zellmer *et al.* 2019; Turan, 2020). Besides, information about invasive alien species distribution and their richness is mandatory by environmental managers and researchers to assist in decision-making on ecosystem restoration, the quantification of detrimental impacts on the recipient ecosystems, and the assessment of the degradation of the habitat (Katsanevakis *et al.* 2011; Blackburn *et al.* 2014; Zellmer *et al.* 2019). Although extensive progress has been done in the monitoring of alien species occurrence, there have been still limited studies for predicting the current and future alien species richness, even for ecologically and commercially important species and regions (Pyšek *et al.* 2008, 2010). Available data on accurate prediction can be used to extend the current geographical information on biodiversity patterns and to facilitate conservation actions and management of alien species. Further, the models used for the predictions would enable alien species mapping

Moreover, alien species spread and richness have a highly dynamic nature. Thus, regular updates are needed in time intervals (Turan *et al.* 2016; Seebens *et al.* 2017; Turan *et al.* 2018). The invasion of alien species to the Mediterranean Basin has both ecological and economic importance that are essential to be addressed, studied, monitored, and forecasted (Yağlıoğlu *et al.* 2014;Galil *et al.* 2015; Doğdu *et al.* 2016; Turan *et al.* 2018). When the invasive species get established in the new environment, they increase in number and spread in the habitat. Puffer fishes are occurring throughout tropical and subtropical areas of the Indian, Pacific, and Atlantic Oceans (Galil *et al.* 2015; Turan *et al.* 2017; Doğdu and Turan, 2021) and are also a good indication of the tropicalization of the Mediterranean fish fauna. In the last decades, puffer fish species recorded in the Mediterranean rose from 3 to 11 species (Matsuura *et al.* 2015; Ergüden *et al.* 2017; Turan *et al.* 2018).

Silver-cheeked toadfish *Lagocephalus sceleratus* is one of the worst invader fish species (Zenetos *et al.* 2012; Otero *et al.* 2013; Farrag *et al.* 2016) that has negative impacts on public health, biodiversity, and fishery (Ragkousis *et al.* 2020; Doğdu *et al.* 2021; Turan, 2022). *L. sceleratus* is a hazardous fish to human health since it is toxic to eat due to having lethal tetrodotoxin (TTX) (Doğdu *et al.* 2019; Akbora *et al.* 2020). Moreover, *L. sceleratus* has negative impacts on biodiversity due to being untargeted and also creates problems for fishermen that damage passive fishing gears and fish entangled in the fishing gears, causing economic losses (Turan 2010; Ünal *et al.* 2015; Farrag *et al.* 2016). There is a limited modelling study on the estimated distribution and richness of *L. sceleratus*. Coro *et al.* (2018) predicted the range expansion of *L. sceleratus* in the Mediterranean Sea with AquMaps modeling and suggest that *L. sceleratus* will continue its rapid spread and likely have a high impact on fisheries.

This study aims 1) to predict the geographic distribution of *L. sceleratus* in the Mediterranean, 2) to forecast changes in distribution patterns in response to climate change, 3) to assess the relative importance of environmental factors influencing the spatial distribution of *L. sceleratus* that may assist policymakers and regional managers in generating a proper implementation for handling its invasion.

MATERIALS AND METHODS

Species data: In this study, coordinates of 98 occurrence records of the invasive silver-cheeked toadfish *L. sceleratus* across the Mediterranean Sea were obtained, describing the invasive distribution from 16 countries. The occurrence points were obtained from the published and grey literature, and also from personal observations (Yağlıoğlu *et al.* 2011; Dulčić and Dragičević, 2014; Šprem *et al.* 2014; Kara *et al.* 2015; Farrag *et al.* 2016; Ergüden *et al.* 2017; Akyol and Ünal, 2017; Turan *et al.* 2018). If only localities were given as occurring in a study, Google Earth was applied to approximately gather coordinates of the given localities. The occurrence records used were also checked for correctness in QGIS (v3.1) before using it in the modelling (Fig. 1), and geo-records with coding errors, adjoining records, and duplicate records on the same region were excluded. The data were divided into two sets, training and testing. The training set used in the present study belonged to the puffer fish's distribution habitats comprising highly abundant eastern Mediterranean, which was similar to their native occurrence. Then the coordinates from the Egyptian coast were used as a test set to verify the models.

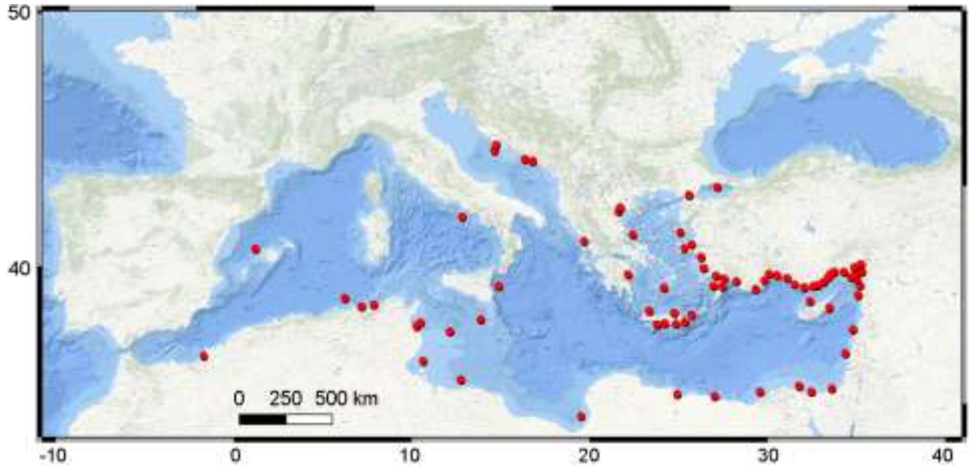

Fig. 1. The used occurrence points of the silver-cheeked toadfish *L. sceleratus* in the Mediterranean (Obtained from QGIS Esri Ocean).

Environmental predictor variables: Marine climatic variables were collected from the Bio-ORACLE (Ocean Rasters for Analysis of Climate and Environment) (Assis *et al.* 2018) and MARSPEC (Sbrocco and Barber, 2013) global databases, which have been commonly used in forecasting the current and future distribution of species. The ORACLE dataset provides an array of climatic data at a spatial geographic resolution of 5arcmins (9.2 km) in the ESRI ASCII format. Multicollinearity among the predictor variables used is not required by predictive models. Therefore, Spearman's rank correlation was used to test available predictor variables for multicollinearity. In addition, presence-only SDM methods generally use background or pseudo-absence points for constructing models (Franklin 2010). Therefore, a set of 1.500 randomly sampled pseudo-absence records within the study area in the benchmark dataset were included.

IPCC A1B emissions scenario (intermediate emission scenarios balanced across all sources) for 2100 (IPCC, 2013)was used for the future distribution forecasting that the future layers of only five candidate marine environmental variables (BO_salinity, BO_sstmax, BO_sstmin, BO_sstrange, BO_sstmean) were available for this scenario. Therefore, in order to use more ecological variables in the current modellings, the present and future distribution modellings were run separately.

Bioclimatic modeling: The correlative models in species distribution compare the presence or abundance of a given species with regional habitat information and map the probability of the presence of the species across given coordinates on the map. Fifteen modeling techniques used in the sdmpredictor package were tested to relate the distribution of *L. sceleratus* in the Mediterranean environmental conditions: Generalized linear model (glm), climate-envelope models (bioclim, bioclim.dismo), fit a generalized linear model via penalized maximum likelihood (glmnet), recursive partitioning and regression trees (rpart), mahalanobis model in dismo (mahal.dismo), generalized additive model (gam), multiple adaptive regression splines (mars), flexible discriminant analysis (fda), maximum entropy (maxent), model occurrence probability using presence-only data (maxlike), mixture and flexible discriminant analysis (mda), create and train a multi-layer perceptron (mlp), create and train a radial basis function (rbf), random forest (rf), support vector machines (svm) were chosen as implemented in the SDM package to find the best model that suits our geographic data (Naimi and Araújo, 2016). Pseudo-absence records (1.500) were randomly generated within the Mediterranean Sea and its adjacent waters since these techniques generally require a set of environmental variables to contrast with the ones where the species occur (Guisan *et al.* 2017).

The area under the receiver operating characteristic curve (AUC) and the true skill statistics (TSS) were used for assessing the accuracy of the methods. The AUC ranges from 0 to 1, and the TSS range from -1 to 1 (Araújo *et al.* 2005). Model algorithms with TSS value below 0.70 and AUC value below 0.80 were considered as bad accuracy and excluded from further analyses (Zhang *et al.* 2015), and only modeling algorithms with TSS score above 0.7and AUC value above 0.80 was included in the subsequent modeling procedure that uses all occurrence and pseudo-absence data for acquiring prediction (Manel *et al.* 2001). Weighted ensemble averaging of the model replicates was built for forecasting the distribution of *L. sceleratus*, which performs better than any individual model since the various errors of the used models were averaged out.

The relative importance of each environmental variable in forecasting the distribution pattern of *L. sceleratus* was also evaluated, which calculates the Pearson correlations between predictions using all predictor ecological variables in the model (Graham *et al.* 2011).All data processing was performed in Rv3.6.1(R Core Team, 2021), and the modelling algorithms used in the present study were performed with the default settings of sdmpredictors and sdm packages (Manel *et al.* 2001; Araújo *et al.* 2005; Graham *et al.* 2011; Zhang *et al.* 2015; Bosch *et al.* 2016; Naimi and Araújo, 2016; Guisan *et al.* 2017) that 15.000 as the maximum number of background absences, 0.00001 convergent thresholds, and 500 as the maximum numbers of iterations, and a logistic output resenting a continuous presence probability ranging from 0 to 1.

RESULTS AND DISCUSION

Model performance: Model run success was 100% for 15 models, available in the sdmpredictors package, and the AUC values ranged from 0.61 for rpart to 0.99 for rf, and the TSS values varied from 0.41 for mlp to 0.95 for rf. Based on the cutoff values of TSS and AUC scores, the seven modelling algorithms (bioclim, bioclim.dismo, gam, glm, mars, maxlike, rf) out of the 15 models were above the cutoff value of 0.8 that were used for the further ensemble modeling and descriptive analysis (Table 1). For the future prediction, the ensemble method with the seven models was also used, and AUC values ranged from 0.90 for mars to 0.95 for rf, and TSS values ranged from 0.90 for gam to 0.80 for mars. The average TSS and AUC values were 0.94 (±0.02) and 0.85 (±0.05) for the current and 0.92 (±0.02) and 0.82 (±0.02) for the future ensemble modelings, respectively. Features, advantages, and limitations of each applied method for predicting the current and future distribution of *L. sceleratus* were also listed in Table 2.

Table 1. The tested model performances of *L. sceleratus*. *, indicate the models used for the current and future predictions.

Methods\Statistics	Current		Future	
	AUC	TSS	AUC	TSS
bioclim*	0.82	0.71	0.85	0.76
bioclim.dismo*	0.84	0.73	0.81	0.72
gam*	0.95	0.81	0.87	0.71
glm*	0.94	0.83	0.80	0.78
mars*	0.92	0.77	0.82	0.75
maxlike*	0.93	0.82	0.84	0.78
rf*	0.99	0.95	0.90	0.86
glmnet	0.74	0.65		
mahal.dismo	0.85	0.61		
fda	0.84	0.62		
mda	0.81	0.56		
mlp	0.66	0.41		
rbf	0.83	0.57		
rpart	0.61	0.44		
svm	0.74	0.57		

Table 2. Feature, advantages, and limitations of each applied model.

Model abbreviation	General class	Species data	Advantages/Limitations	References
glm	Regression	Various	Generalized additive models allow smoothed data-driven functions	Hastie *et al.* (2009); Mellert *et al.* (2011)
bioclim	Climate envelope	Presence	Delimits climate envelope only using presence data, sometimes using percentiles; prediction from most extreme (limiting) variable; having the advantage of being the first model for predicting species distribution	Busby (1991); Booth *et al.* (1988)
bioclim.dismo	Climate envelope	Presence	It generally does not perform as good as some other modelling methods and is unsuited for predicting climate change effects; easy to understand and use.	Elith *et al.* (2006); Hijmans and Graham (2006)
gam	Regression	Various	Generalized additive models allow smoothed data-driven functions	Hastie *et al.* (2009); Mellert *et al.* (2011)
mars	Non-parametric regression	Absence	Works well with a large number of predictor variables; automatically detects interactions between variables; an efficient and fast algorithm, despite its complexity; robust to outliers; susceptible to overfitting; more difficult to understand and interpret than other methods; not good with missing data	Leathwick *et al.* (2006); Elith *et al.* (2006)
maxlike	Regression	Presence	For smaller data sets, the uncertainty in predicted occurrence probability was very large, due to the inherent limitations of presence-only data; not as flexible, arrangements need to be specified; logit-linear model which first ensures that the predicted value is a real probability value	Merow and Silander (2014)
rf	Regression	Various	Receiving much attention in forecasting the effect of climate change on species distribution because growing a large number of small trees limits the generalization error; provides a measure of variable importance in the modelling	Hastie *et al.* (2009); Broennimann *et al.* (2007)

Variable contribution: For the current distribution modeling of *L. sceleratus*, 19 candidate marine environmental variables from Bio-Oracle and MARSPEC were tested, and 9 variables out of the 19 input variables showed collinearity problems in the prediction analyses, which were excluded for further analyses. Finally, spatial data referring to the remaining 10 marine environmental variables were retrieved: mean sea surface temperatures (BO_sstmean), salinity (BO_salinity), pH (BO_ph), maximum depth of the seafloor (BO_bathymax), maximum seawater temperature at minimum depth (BO2_tempmax_bdmin), maximum seawater temperature at maximum depth (BO2_ tempmax_bdmax), minimum light at mean depth bottom (BO2_lightbotmin_bdmean), East/West aspect derived from bathymetry (MS_biogeo01_aspect_EW_5m), North/South Aspect derived from bathymetry (MS_biogeo 02_aspect_NS_5m), satellite measures of sea surface temperature (MS_biogeo16_sst_range_5m). The raster layers of the used climatic data obtained from sdmpredictors are given in Fig. 2.

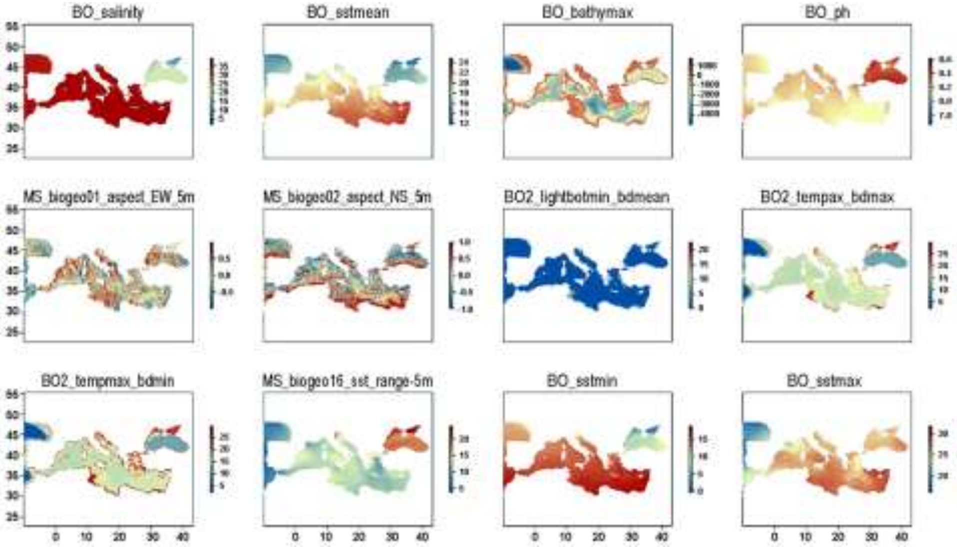

Fig. 2. The present raster layers of the used climatic data from the Bio-ORACLE and MARSPEC.

The ten predictor variables contributed in different degrees to the model predictions, and the maximum seawater temperature at minimum depth (BO2_tempmax_bdmin) contributed the most to the model predictions, followed by the salinity (BO_salinity) and a maximum depth of the seafloor (BO_bathymax) (Fig. 2). Therefore, the maximum seawater temperature at minimum depth explained strong biological importance to the adaptation of *L. sceleratus* with extreme environmental factors. For future distribution modelling, the available five candidate marine environmental variables (BO_salinity, BO_sstmax, BO_sstmin, BO_sstrange, BO_sstmean) were used for the prediction of future distribution. Only 3 variables (BO_salinity, BO_sstmax, BO_sstmin) revealed no collinearity problems in the prediction analyses which were used for the future projections in which the salinity contributed the most to predictions of the model, followed by the minimum and maximum sea surface temperature (Fig. 3). Thus, the salinity and temperature explained strong biological importance to the future adaptation of *P. miles* with extreme environmental factors. The response curves of *L. sceleratus* to BO_sstmean, MS_biogeo01_aspect_EW_5m, MS_biogeo 02_aspect_NS_5m, and BO_salinity were relatively higher (Fig. 4).

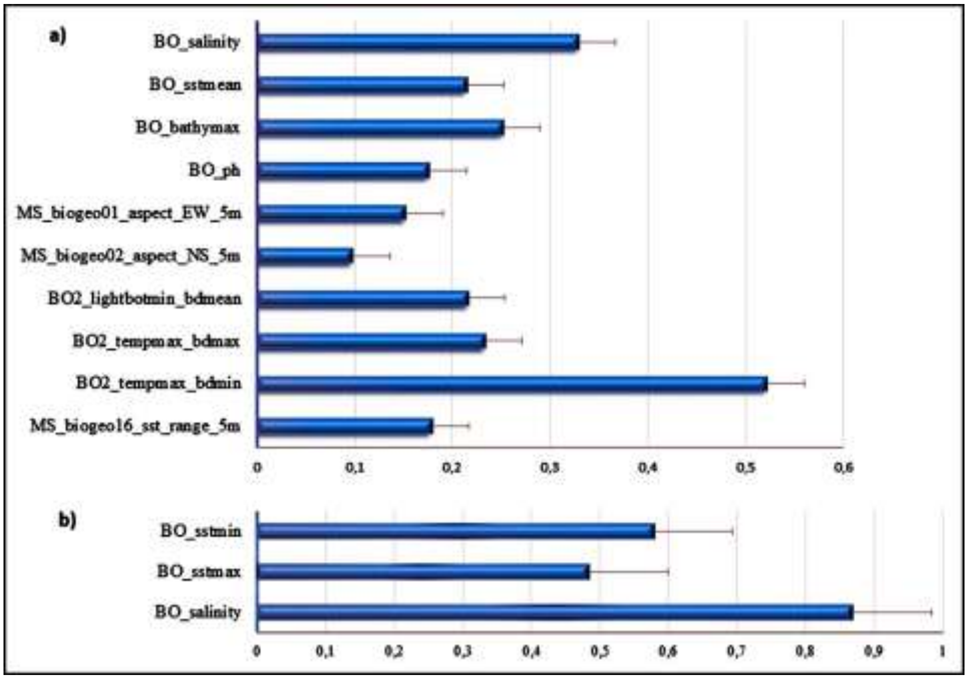

Fig. 3. The mean relative variable importance of each variable for current (a) and future (b) predictions of *L. sceleratus* in the Mediterranean Sea.

Current potential distributions: All of the collected occurrence records in the Mediterranean were within the predicted suitable range of the ensemble models. The ensemble forecasting of suitable habitats for *L. sceleratus* under the current climate was presented in Fig. 5 where *L. sceleratus* dominantly occurred in the middle and east parts of coastal areas of the Mediterranean, indicating the high suitability of these areas for *L. sceleratus*. There was no predicted current suitable habitats and distribution pattern of *L. sceleratus* in the Black Sea.

Future potential distributions: The results for predicted future suitable habitats and distribution of the invasive *L. sceleratus* under future climate scenario (A1B) according to the ensemble projections with seven methods revealed that *L. sceleratus* increase the range of distribution dominantly to the central and west part of the Mediterranean in spatial extent, indicating high suitability of these areas for future distribution of *L. sceleratus* (Fig. 6). There was no predicted future suitable habitats and distribution of *L. sceleratus* in the Black Sea.

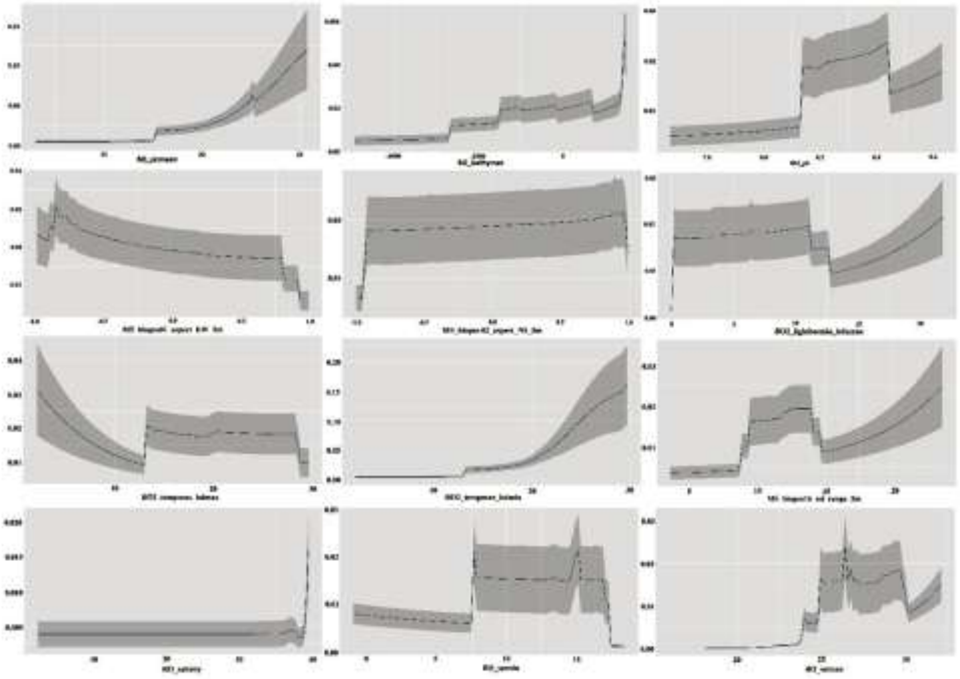

Fig. 4. Averaged response curves of *L. sceleratus* to the environmental variables for the used seven models. The greyed area around the line indicates deviation (95% confidence intervals) from the average.

DISCUSSION: The ensemble forecasting framework implemented with seven bioclimatic modelling techniques based on current records of occurrence accurately predicted the invaded range of invasive silver-cheeked toadfish *L. sceleratus* and suggested that the seawater temperature, salinity and maximum depth of the seafloor are relatively the most important determinants of its distribution at the Mediterranean range margin. Under future climate scenarios, the ensemble forecasting predicted westward range expansion of *L. sceleratus*, and there is increased future habitat suitability in these regions that were previously described with low suitability. Coastlines in the middle and western Mediterranean are at high risk for a future invasion of *L. sceleratus*.

The temperature variables indicated that it is a very important limiting factor to the range extension of *L. sceleratus* in the Mediterranean (Fig. 3 and Fig. 4). The sea surface temperature, in particular, was also previously reported to be a significant environmental variable as a predictor linked to the global distribution of marine invasive species (Turan *et al.* 2016; Bruno *et al.* 2018). Therefore, the predicted changes in sea surface temperature are causing suitable habitats to shift towards the western Mediterranean, the same was also reported for another invasive species *Pterois miles* in the Mediterranean Sea (Turan, 2020). Moreover, Michailidis (2010) and Rousou *et al.* (2014) reported that

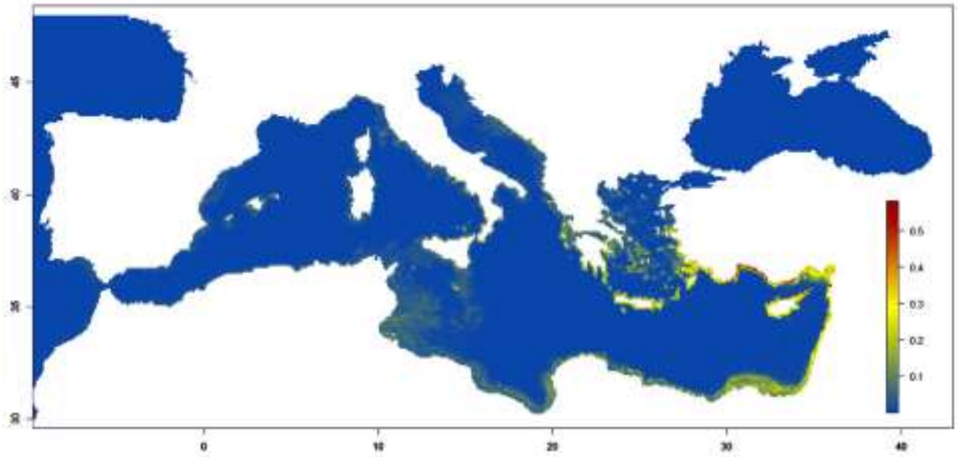

Fig. 5. The predicted current distribution of *L. sceleratus* in the Mediterranean based on unweighted ensemble modeling. The scale bar shows the probability of richness.

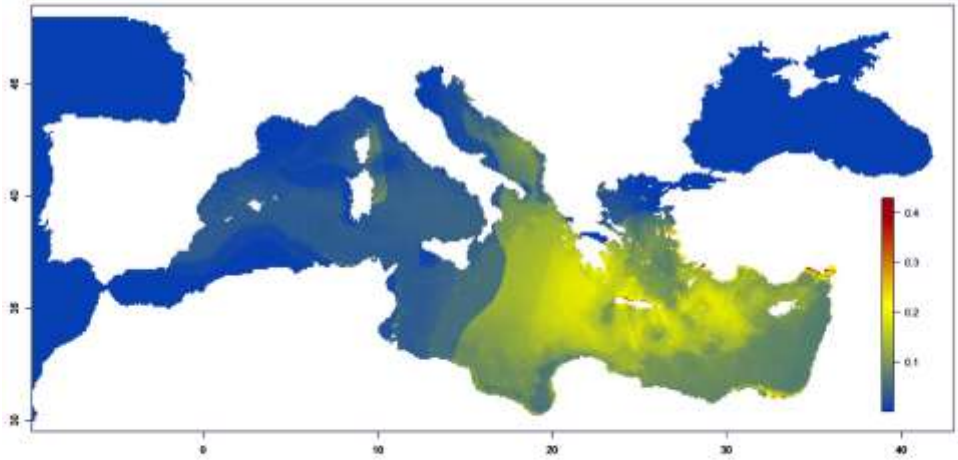

Fig. 6. Predicted future distribution of *L. sceleratus* in the Mediterranean by 2100 under the IPCC climate change scenario A1B.

there might thermal limit for spawning at around 21-22°C of sea surface temperature in the summer, which was the peak spawning period. The expansion of *L. sceleratus* towards the central and northern Aegean has been attributed to anomalously high summer temperatures during the summer of 2007 (Pancucci-Papadopoulou *et al.* 2012). These studies may indicate that seasonal high temperature anomalous in regions may extend their distribution due to the high mobility capacity of *L. sceleratus* which, but, might not be persistent as long as the high temperature stays insistent. The salinity responded as an essential contributing variable to its distribution among the environmental variables. The model showed a high habitat suitability for salinities > 38, indicating that they primarily prefer and persist in higher salinity habitats. On the other hand, the low salinity feature (% 0.18) of the Black Sea may be the main barrier to its expansion for its current and future distribution in the Black Sea since the current salinity (BO_salinity) was distributed over the area of the Mediterranean Sea more or less uniformly (Fig. 2). Therefore, the low salinity feature of the Black Sea (%o 18) also seems to cause BO_salinity to be an important parameter for the current and future distribution of *L. sceleratus* in the Mediterranean. Nevertheless, there has been no study to evaluate how *L. sceleratus* respond to salinity in ex situ or situ settings, and the observed response in the present study can be indirectly relevant to a climatic variable not calculated in the used model. Species response to East/West distribution derived from bathymetry was gradually decreased, in contrast to North/South distribution which was steadily increased. This indicates that the deeper western parts of the Mediterranean restrict its distribution pattern. On the other hand, the increased responsibility to the North/South aspect was congruent with its entrance from the Suez Channel and its northward invasion pathway. The differences in the responses of East/West and North/South aspects indicated that bathymetric differences in the latitudinal and longitudinal aspects of the Mediterranean differentially affect its distribution pattern in the Mediterranean.

Moreover, other factors aside from the climate should also be considered as scale in the modelled predictions (Pearson and Dawson, 2003). Filiz *et al.* (2017) studied the invasiveness of five pufferfish species in the Mediterranean with basic risk assessment scores and indicated that *L. sceleratus* has the highest risk of invasiveness among the pufferfish species, and the factors increasing overall invasiveness scores were; high climate match, tolerance of a wide range of environmental conditions, flexibility in utilizing food resources that support the predicted its distribution in the Mediterranean based on the climate-based models.

The current predictions of *L. sceleratus* dominantly occurred in the middle and eastern parts of coastal areas of the Mediterranean. The most affected countries by the current invasion of *L. sceleratus* seem to be Türkiye, Greece, Cyprus, and the Northeastern part of African countries, Libya, and Egypt. The predicted distribution and abundance of *L. sceleratus* as presented in the used models were also supported by Nader *et al.* (2012), who also reported economic, ecological, and social impacts of *L. sceleratus* in Eastern Mediterranean countries. Coro *et al.* (2018) also studied the current distribution of *L. sceleratus* in the Mediterranean Sea using different modelling techniques that the pattern of predicted distribution is not entirely congruent with the present modeled distribution, especially for the Black Sea. Moreover, unlike Coro *et al.* (2018), the present study provides the environmental drivers, which play an important role in the current and future distribution of *L. sceleratus* in the Mediterranean. Moreover, the future prediction given by Coro *et al.* (2018) was for 2050, but this study provides a prolonged forecast for 2100.

When species distribution modelling are used to predict invasion risk, there is always some level of uncertainty with all models. The presently used model assumes that there is a possibility for the establishment, and fine-scale ecological characteristics such as dispersal via ocean currents or regional biological interactions such as predators, which might be an important driver to where *L. sceleratus* has been able to invade, are not accounted and not included in the present model. The used model reflects the habitat suitability of *L. sceleratus* given any means of introduction and does not directly account for dispersal barriers or specific facilitators.

To make a forecasting about the potential distribution of a species in future habitats, the climatic variables from the Bio-ORACLE for the A1B climate scenarios (A1B is based on lower CO_2, N_2O, CH_4, and SO_2 emissions) were obtained for 2100. For this scenario, only salinity and sea surface temperatures future layers (sstmax, sstmin, sstmean, sstrange) were available. Several ecological variables can affect the distribution of marine species. However, previous studies (Bosch *et al.* 2018; Goldsmith *et al.* 2018) have revealed that a few predictor variables can also correctly predict the distribution of marine species.

The ensemble forecasting under the A1B climate scenarios indicated that suitable environmental conditions for invasive *L. sceleratus* will shift westward surrounding coastal areas such as the Adriatic, Balearic, Ligurian, and Tyrrhenian Seas that the potential distribution of *L. sceleratus* in the east part of the Mediterranean will be weakened by the end of the century.

The studies on SDM have aimed to elucidate important components of uncertainty such as differences between modelling methods (Pearson *et al.* 2006), uncertainty in predictors (Kriticos and Leriche, 2010), bias in species records (Rodda *et al.* 2011),and differences in the usage of parameters (Hartley *et al.* 2006). On the other hand, SDMs are increasingly used in ecology to predict the possible invasive range of alien species. Hitherto, they are sometimes criticized (Lobo *et al.* 2008; Araújo and Peterson, 2012; Jiménez-Valverde, 2012), especially since validation works with independent data are too scarce to measure the predictive accuracy of SDMs. Moreover, retrospective assessment of species invasions allows for controlling the use of SDMs by whether they would have accurately predicted the latest ranges of invasion (Phillips *et al.* 2006; Evangelista *et al.* 2016; Barbet-Massin *et al.* 2018). In the present study, the invasion of *L. sceleratus* indicated that the forecasted climate suitability of independent validation points is adequate and that the geographic extension of *L. sceleratus* is climatically determined and can be accurately predicted by ensemble modeling.

Documenting its current and future distribution of *L. sceleratus* would be crucial for its management strategies and implementations. The predicted spread poses a challenge to the land-use managers in the area which would impact local livelihood. There are various detrimental effects of invasive alien species that cause a great time and monetary loss for the local resource managers to undertake interventions to prevent the spread of the species.

CONCLUSIONS

The ensemble forecasting framework implemented with sevenbioclimatic modelling techniques based on current records of occurrence accurately predicted the invaded range of the invasive silver-cheeked toadfish *L. sceleratus* and suggested that the seawater temperature and maximum depth of the seafloor were relatively the most important determinants of distribution at the Mediterranean range margin. The suitable bioclimatic envelope of *L. sceleratus* under the present study is predicted to widen because of climate change. Previously unsuitable areas in the Mediterranean become suitable for

L. sceleratus, which would have tremendous effects on local biodiversity, livelihood, and public health in the western Mediterranean. Under the future climate scenarios, the ensemble forecasting predicted westward range expansion of *L. sceleratus* and increased suitability in these regions that were previously described with low suitability. Coastlines in the middle and western Mediterranean are at high risk for a future invasion of *L. sceleratus*. The current species distribution modeling provides a risk assessment of the marine protected areas, which are at high risk, and advises the relevant countries about the high requirement to pay attention to its introduction and invasions. Accordingly, prompt, effective actions from resource managers should be undertaken to mitigate its impacts and spread. Control of the stocks of *L. sceleratus* in the eastern Mediterranean can also prolong its range of expansion. The documentation of its current and future distribution would be very crucial for its management strategies and implementations. The predicted spread poses a challenge to the land-use managers in the area which would impact local livelihood. The invasion has a variety of adverse effects that bring about a great deal of time and monetary loss to regional managers to prevent the spread of invasive species (Gürlek *et al.*, 2016; Stamouli *et al.*, 2017).

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