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Modeling the spatial distribution of the ctenophore *Mnemiopsis leidyi* A. Agassiz, 1865 in the Black Sea using a fuzzy rule-based system

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Species distribution models can predict species occurrences in areas where no data is available by finding relationships between occurrences and environmental parameters. In this study, we applied a fuzzy rule-based system to model the spatial distribution of Mnemiopsis leidyi *in the Black Sea and predict the probability of its presence throughout the sea. Six variables were used as predictors, including water turbidity, organic and inorganic particulate carbon, photosynthetically active radiation, light absorption by phytoplankton, sea surface temperature, and chlorophyll-a concentration. The results revealed a 0.807 accuracy of the model based on the confusion matrix. The results also showed that photosynthetically active radiation and sea surface temperature were the most important predictors shaping the distribution of this species.*

The findings also showed that the northern Black Sea was with the highest probability of presence, especially in Ukraine and Russia's coastal areas. In the coastal areas of Turkey, the highest presence probability was found near Rize, Trabzon, Ordu, and from Sinop to Zonguldak. Therefore, continuous monitoring of the Turkish coastal area is crucial to better understanding the effects of climate change and anthropogenic influences on the further distribution patterns of this invasive ctenophore in the southeastern Black Sea.

Key words: Non-indigenous invasive species; conservation; management; remote sensing; model

INTRODUCTION

Climatic changes and adverse anthropogenic effects have altered marine ecosystems (HUGH-GULDBERG & BRUNO, 2010), causing ecological imbalance and introducing new species. Semi-enclosed marine ecosystems such as the Black Sea, the Baltic Sea, and the Caspian Sea are more affected by such changes (JAVIDPOUR *et al*., 2006; OĞUZ *et al*., 2008; JASPER *et al*., 2018). In particular, opportunistic gelatinous macro-zooplankton species have caused the food chain of "phytoplankton-zooplankton-small pelagic fish" in the Black Sea ecosystem to change into "phytoplankton-zooplankton-gelatinous zooplankton" (KIDEYS, 2002). The gelatinous *Mnemiopsis leidyi*, introduced into the ecosystem in the late 1980s and soon became dominant in the Black Sea, was shown to have negative effects on the food web. In the Black Sea, which was already affected by various effects, especially overfishing and climate change, this ctenophore has led to a considerable decrease in fish catches (KIDEYS, 2002; SHIGANOVA *et al*., 2004; MUTLU, 2009). Efforts to determine its impact on the Black Sea ecosystem start with monitoring the regional and temporal distribution and abundance changes. Therefore, it is crucial to determine the distribution pattern of this species in the whole Black Sea and to predict its possible future variations using underlying biological, physical, and chemical environmental data.

Biodiversity distribution models can predict areas for species occupation by finding relationships between occurrence and relevant environmental parameters (LEHMAN *et al*., 2002), which is widely applied in marine environments (KELLY *et al*., 2001; SEQUEIRA *et al*., 2014, 2016). These models can predict species occurrence patterns in areas where no data is available (ROBERTSON *et al*., 2003). Hence, the development of such models can provide cost-effective tools for conservation and management purposes. With this aim, the present study applies a fuzzy rule-based system to model the spatial distribution of *M. leidyi* in the whole Black Sea and figure out how likely it is to be in places where no data is available, especially in the vulnerable coastal area of the Turkish part of the southeastern Black Sea, where no data is available.

MATERIAL AND METHODS

Environmental data

Environmental data were obtained from the Modis project's NASA website (NASA Goddard Space Flight Center, Ocean Ecology Laboratory, 2021). The following annually-averaged environmental variables were downloaded: (1) remote sensing reflectance at 645 nm (r645 [sr^{-1}]) considered as water turbidity based on CHEN *et al.* (2007); (2) organic and inorganic particulate carbon (POC, PIC [mol m^{-3}]); (3) photosynthetically active radiation (PAR [Einstein m^{-2} day^{-1}]); (4) remote sensing reflectance at 443 nm (phy [m^{-1}]) indicating light absorption by phytoplankton; (5) sea surface temperature at day- and night-time (SSTd, SSTn [°C]); and (6) chlorophyll-a concentration (chl-a [mg m^{-3}]) as an indicator of primary production. Turbidity is a crucial factor for filter-feeding organisms. Inorganic carbon indicates the amount of particles composed of $CaCO_3$ affecting the optical properties of water and hence photosynthesis, and may also be an index of ocean acidification affecting calcifying planktons. PAR is the spectra of light involved in photosynthesis and thus primary productivity.

The reflectance at 443 nm indicates the amount of light absorbed by phytoplanktons involved in photosynthesis. The SSTd and SSTn are sea surface temperatures and influence the rate of metabolism of poikithermic organisms like *Mnemyopsis*. The annually-averaged data from the variables was in the NetCDF format (with an extension of nc). All data layers were imported into R (version 3.5.15) using the "raster" package, then stacked using the function stack and their data extracted for further calculations (HIJMANS, 2022).

Species data

The presence data for *M. leidyi* in the Black Sea was obtained from the Ocean Biogeographic Information System website (OBIS, 2019).

Data analysis

There were a few presences of *M. leidyii* each year. In addition, a high percentage of duplicated coordinates have been reported as the presence locations of *M. leidyi*. As a result, data from all sampling years (2002-2012) were used to construct a model. All remotely-sensed data for all years was averaged over each combination of the variables and pixels.

We used Ishibuchi's method based on the hybridization of GCCL and Pittsburgh (RIZA *et al.*, 2015). This method is based on a genetic algorithm. To avoid over-fitting, the method was performed using the caret package in R (KUHN, 2021), which can perform many predictive modeling approaches with various cross-validation methods. The caret package validates the models. However, only 70% of the total data was used for modeling and considered as training data. The rest of the data was used as testing data. The model's performance was examined using accuracy as indicated by the confusion matrix, the Cohen's Kappa statistic, and the receiver operating characteristic curve (ROC; KUHN AND JOHNSON, 2013). The importance of each remotely-sensed variable on the presence of *M. leidyi* was determined using the varImp function of the caret package in R (KUHN, 2021).

RESULTS

After the duplicated sampling points were removed, the sampling points used for modeling mainly belonged to the northern Black Sea (Fig. 1). The minimum, maximum, and average of the environmental parameters are presented in Table 1. Among the variables, POC had the highest values and hence the largest range. PIC had the lowest values with a narrow range. Also, X645 has a narrow range, indicating similarity, showing a low variation in turbidity across the Black Sea. SSTn had a greater variation than its daytime counterpart. Chlorophyll concentration had great variation, ranging from almost nil to 0.40 mg m, indicating a great variation in the primary productivity of the sea. PAR and Phy had a moderate variation in the sea.

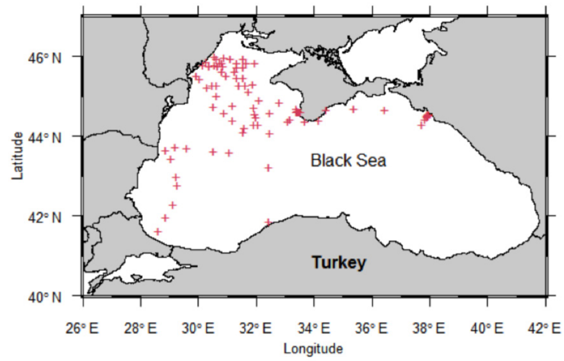

Fig 1. The selected sampling points after removing the duplicated sampling coordinates.

Table 1. The minimum, maximum and average of the environmental variables used for modelling

Variables	**minimum**	**Maximum**	**Average**
PIC	0.0001	0.0087	0.0010
Chl	0.6037	41.5984	2.5112
PAR	24.2639	34.0998	30.3707
Phy	0.0123	0.3972	0.0420
POC	0	1522.0517	290.6556
SSTd	17.8941	28.7255	22.1846
SSTn	0.3109	22.6382	18.8347
X645	0	0.0162	0.001

The temporal variation (mean ± standard deviation [SD]) of environmental variables is depicted in Fig. 2. Chl, Phy, POC, and X645 were almost stable during the study period. PIC, PAR, POC, SSTd, and SSTn fluctuated over time, with the greatest fluctuation belonging to SSTd. The average of the environmental variables is depicted in Fig. 3. The greatest values of Chl, Phy, and X645 were restricted to the northern Black Sea. No spatial pattern was detectable for the rest of the environmental variables.

According to the model results, PAR was the most important variable influencing the distribution of *M. leydyi* in the Black Sea (Table 2), followed by sea surface temperature. Chlorophyll concentration was the least important factor. The model accuracy based on the confusion matrix was 0.807 (Table 3). The ROC of the model fitted on the training and testing data was 1 and 0.962, respectively. ROC is the area under a curve that indicates the quality of the model with a maximum of 1. A greater value indicates

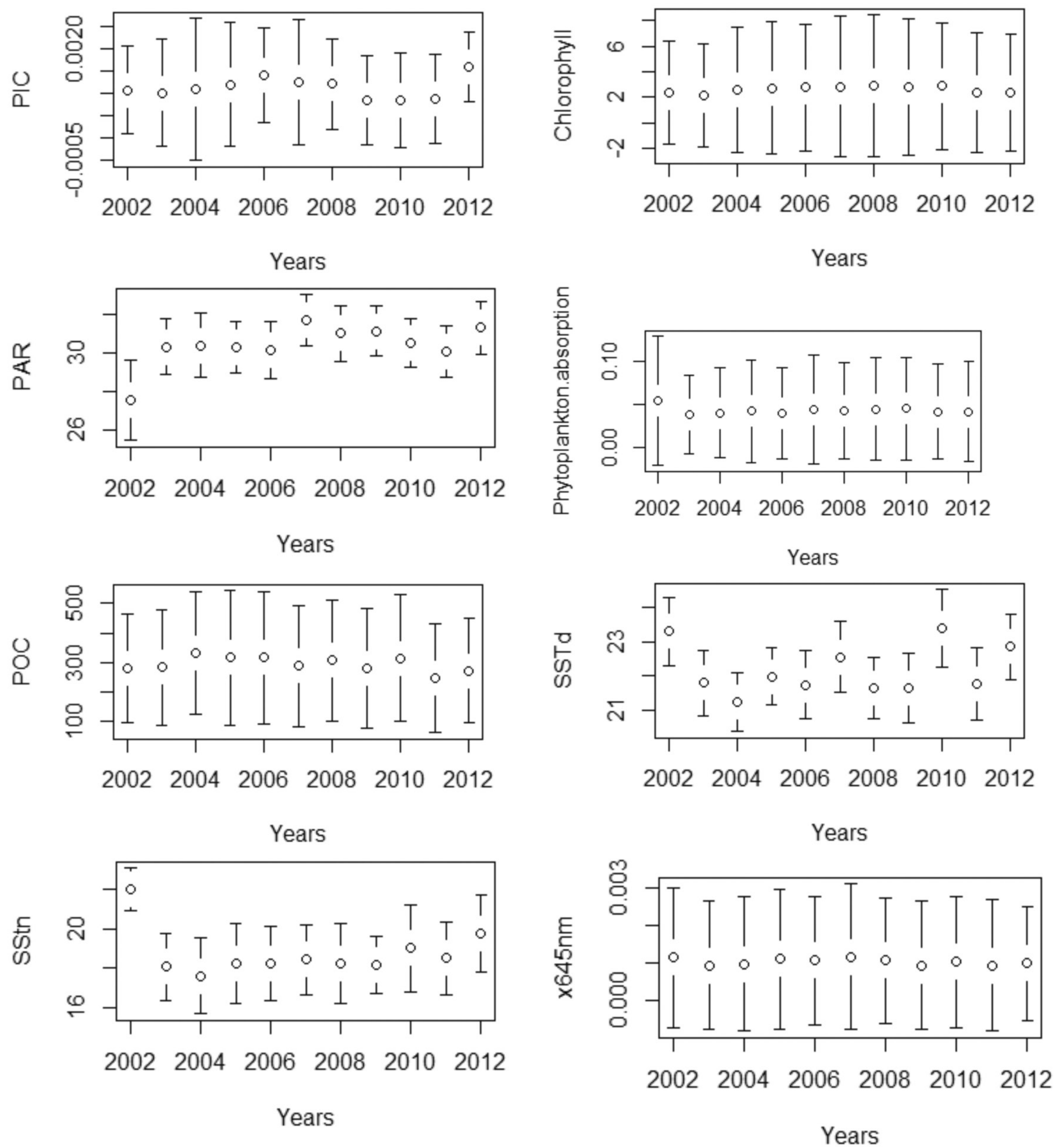

Fig 2. Mean (± SD) *of the environmental variables over 2002-2012 period*

the higher predictability of a model. Therefore, the model created for the present data had a high ROC and predictability. The Cohen's Kappa of the training data set was 0.560. Cohen's Kappa is a statistic that indicates the agreement between two rates on the same data, with values within 0.3 to 0.5 showing acceptable agreement.

Based on the predictors, the northern Black Sea had the highest probability of the presence of *M. leidyi* (Fig. 3). In particular, the coastal areas of Ukraine and the Russian part of the Black Sea had the greatest presence probability of this species, while the middle and southern parts of the Black Sea had the smallest probability of presence. Among the southern areas, the coastal areas of Turkey, i.e., Rize, Trabzon, Ordu, and from Sinop to Zonguldak, had the highest presence probability.

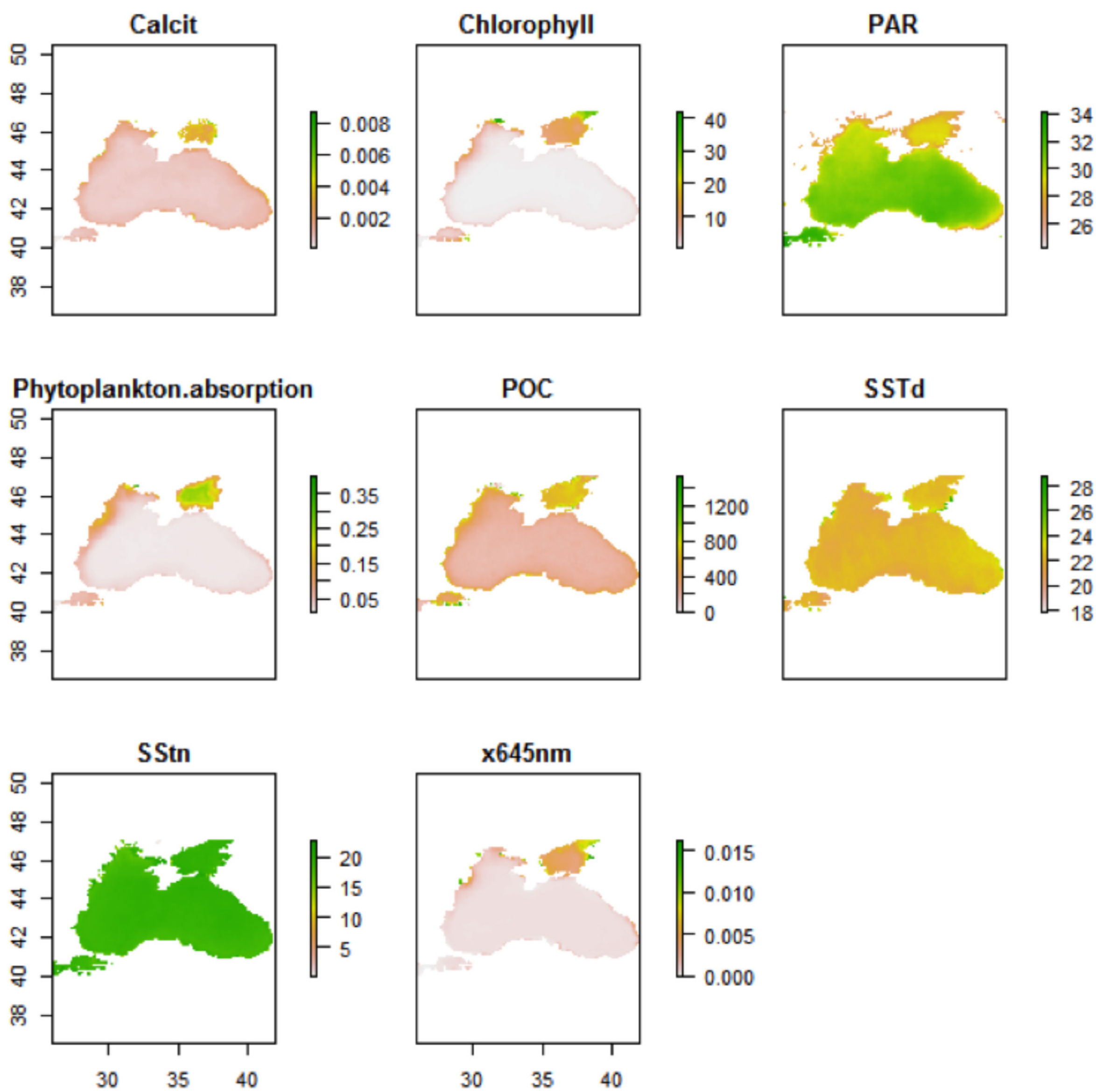

Fig 3. The values of remotely-sensed data averaged over 2002-2012 period

*Table 2. The importance of the remotely-sensed variables on the spatial distribution of M*nemiopsis leidyi. *For information about variables refer to the text.*

Variables	**Overall importance**
PAR	100.000
SSTd	61.189
x645nm	30.816
SStn	17.934
Calcit	6.283
Phy	4.599
POC	3.884
Chl	0.000

Table 3. The confusion matrix and accuracy of the model

		Reference		Accuracy
		0	1	
Prediction	0	50.7	9.3	0.807
	1	10.0	30.0	

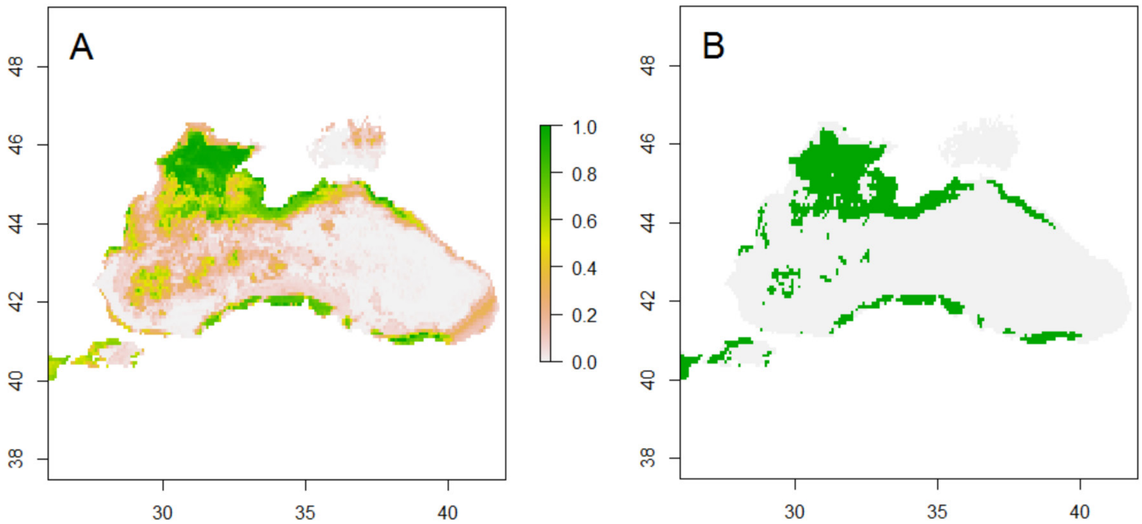

Fig 4. (A) The predicted probability of presence of Mnemiopsis leidyi in the Black Sea, and (B) the presence points of the M. leidyi *(points with presence probability > 0.5)*

DISCUSSION

Mnemiopsis leidyi impacts strongly the zooplankton community in the Black Sea (BIRINCI ÖZDEMIR *et al*., 2018; SHIGANOVA *et al*., 2019). It is a competitor of planktivorous fish and predators of their developmental stages (KIDEYS, 2002; GUCU, 2002) and may have a negative impact on biodiversity in national protected areas in the Black Sea (SHIGANOVA *et al*., 2019). So, figuring out where it will be in the Black Sea, which is changing due to the effects of humans, global climate change, and overfishing, is important for finding risks and coming up with management plans and ways to reduce them.

Mnemiopsis leidyi is highly adaptable, surviving at temperatures ranging from 3 to 29 °C and salinities ranging from 5 to 40 psu (PURCELL *et al*., 2001). Its population growth been reported at low temperatures and salinities in northern European seas (JASPERS *et al*., 2018). In most studies, temperature, available zooplankton prey, and salinity were identified as the determining factors for maintaining ctenophore populations (FINENKO *et al*., 2006; SHIGANOVA *et al*., 2019). However, chlorophyll-a concentration did not influence the distribution of ctenophores in the lagoon system of southeast France (MARCHESSAUX *et al*., 2020). DELPY *et al*. (2016) observed the opposite situation in the Northwestern Mediterranean lagoons. In the lower salinity conditions of the Caspian and Azov seas, higher weight-specific reproduction than in the Black Sea was reported (SHIGANOVA *et al*., 2004).

Our results showed that PAR (photosynthetically active radiation) and sea surface temperature were the most important factors for the spatial distribution of *M. leidyi* in the Black Sea during the investigated decade. Such findings may indicate a side-effect of climate change, with an expected temperature rise, in ecosystems where invasive cryophobic species may dominate, resulting in a great change in community structure. SIAPATIS *et al*. (2008) also found a higher probability of *M. leidyi* presence in the lower values of PAR combined with the lower values of SLA (sea level anomaly), which agrees with our study as the model predicted a high probability of presence in the northern Black Sea where PAR was at the lowest. Aligned with our findings, temperature has already been shown as an effective factor influencing the bloom of *M. leidyi* (KREMER, 1994; SULLIVAN *et al.*,2001). The reflectance at 645nm is an index of turbidity (CHEN *et al*., 2007). In the present study, while turbidity was the next important factor influencing the presence of *M. leidyi*, it had a weak effect in accordance with BAGHERI *et al*. (2021). According to the model, chlorophyll concentration was the least determinant of the presence of the ctenophoran.

However, KIDEYS *et al*. (2008) and BAGHERI *et al*. (2021) found a positive relationship between presence of *M. leidyi* and chlorophyll concentration in the Caspian Sea. Such difference in our findings with those of others may be related to the heterogeneous spatial distribution of chlorophyll concentration in the Caspian Sea, as illustrated in KIDEYS *et al*. (2008). In contrast to the Capsian Sea, chlorophyll concentration had almost uniform distribution in the Black Sea, suggesting that this variable was not a limiting factor for the ctenophoran.

The northern Black Sea, particularly the coastal areas of Ukraine and Russia, had the highest probability of *M. leidyi* presence, whereas the middle and southern parts, i.e., the coastal areas of Turkey, had limited presence. These results are in accordance with the reported distribution of *M. leidyi* in the Black Sea (KAMBURSKA *et al*., 2006). However, continuous monitoring of the coastal area of the Black Sea in the Turkish part is crucial to a better understanding of the climatic changes and anthropogenic effects that may influence the distribution pattern of this invasive species in these areas. Understanding the risk of impacts from introducing an exotic species is an efficient management tool for conservation planning (ÇİÇEK *et al*., 2022). As a successful invader, *M. leidyi* is an important problem for planktonic communities in the Black Sea and for all ecosystem components that it affects indirectly. Estimating how *M. leidyi* might grow and spread in the Black Sea will help decide what to do about things that will make the species' effect on the ecosystem worse.

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Modeliranje prostorne raspodjele verbaša morskoga oraha *Mnemiopsis leidyi* (A. Agassiz, 1865) u Crnom moru korištenjem neizrazitog upravljanje

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SAŽETAK

Modeli raspodjele vrsta mogu predvidjeti pojavu vrsta u područjima gdje nema dostupnih podataka pronalaženjem odnosa između pojava i parametara okoliša. U ovoj studiji smo primijenili nejasan sustav temeljen na pravilima za modeliranje prostorne distribucije *Mnemiopsis leidyi* u Crnom moru i predviđanje vjerojatnosti njegove prisutnosti u cijelom moru.

Šest varijabli korišteno je kao prediktori, uključujući zamućenost vode, organske i anorganske čestice ugljika, fotosintetsko aktivno zračenje, apsorpciju svjetla od strane fitoplanktona, temperaturu površine mora i koncentraciju klorofila a. Rezultati su otkrili točnost modela od 0,807 na temelju zabune matrice. Rezultati su također pokazali da su fotosintetski aktivno zračenje i temperatura površine mora najvažniji prediktori koji oblikuju distribuciju ove vrste.

Nalazi su također pokazali da sjeverno Crno more ima najveću vjerojatnost prisustva, posebno u Ukrajini i obalnim područjima Rusije. U obalnim područjima Turske najveća je vjerojatnost prisutnosti utvrđena u blizini Rizea, Trabzona, Ordua i od Sinopa do Zonguldaka. Stoga je kontinuirano praćenje turskog obalnog područja ključno za bolje razumijevanje učinaka klimatskih promjena i antropogenih utjecaja na daljnje obrasce distribucije ovog invazivnog ctenofora u jugoistočnom Crnom moru.

Ključne riječi: alohtone invazivne vrste; očuvanje; upravljanje; daljinsko očitavanje; model