Environmental Sciences Europe

RESEARCH

Open Access

Present and future habitat shifts of the most important commercial fish species in the Black Sea under climate change

Serkan Gül[1], Yusuf Ceylan[2*] and Göktuğ Dalgıç[2]

Abstract

The Black Sea is unique due to its semi-enclosed area and anoxic layer. However, changes in ecosystem conditions due to climate change in recent years threaten the viability of fish populations. This study focuses on estimating the future distribution and habitat losses of commercial fish species in the Black Sea under climate change. The results reveal that the decline in suitable habitats for all species is reaches considerable levels in the 2030–2040 and 2090–2100 projections of both scenarios (SSP1–1.9 and SSP5–8.5). The future of the Black Sea ecosystem is under the threat of climate change. Countries and unions bordering the Black Sea should develop and implement a common management plan to control anthropogenic effects through international cooperation.

Keywords Black sea, Fisheries, Ecological niche modelling, Maxent

Background

The Black Sea is a unique ecosystem due to some of its physical and structural features (semi-enclosed area and anoxic layer) [1, 2]. Especially small pelagics (horse mackerel, anchovy and sprat) and benthic fish (red mullet, whiting and turbot) are commercially exploited. According to the statistics of the General Fisheries Commission for the Mediterranean (GFCM) (Mediterranean and Black Sea) Catch Production Quantity (1970–2021) published by the Food and Agriculture Organization of the United Nations, these are the most captured species in the Black Sea and constitute 81% of the annual production. [3]. Türkiye exploited the largest area with the largest fishery fleet in the Black Sea region and both Food and Agriculture Organization (FAO) and Turkish statistics indicate the annual production amounts of commercial species are in a fluctuating downward trend [4, 5]. The reasons for this decrease can be listed as overfishing, weaknesses in the fisheries management plan, such as selectivity problems, technical deficiencies, bycatch, and inadequate control [6–8]. In addition, many fishing stocks are operated by fleets with high fishing capacity. Usage of more efficient fishing gears and equipment negatively affects the balance between the capacity of available resources and fishing power [9].

In recent years, the effects of changing ecosystems due to climate change have been added to the always-discussed fishing problems (discard, overfishing, selectivity, invasion, etc.) by the scientists [2]. Changing ecosystem conditions should be considered a threat to the sustainability of fish populations. Some fish stocks are at unsustainable levels due to overexploitation; whether they will cope with climate change can be a matter of concern [3]. In aquatic ecosystems, progressing changes in water temperature depending on atmospheric temperature are considered the first signs that the ecosystem will be affected by climatic conditions. Accordingly, it has been reported that seasonal temperature averages affect the concentrations of some nutrients in the following periods

*Correspondence:
Yusuf Ceylan
yusuf.ceylan@erdogan.edu.tr
[1] Department of Biology, Faculty of Arts and Sciences, Recep Tayyip Erdoğan University, 53100 Rize, Türkiye
[2] Faculty of Fisheries, Recep Tayyip Erdoğan University, 53100 Rize, Türkiye

[10–12]. Since the change in nutrients will affect primary productivity, it may be considered as the beginning of the disruption in the food chain. The Black Sea has previously experienced the effects of eutrophication due to increased nutrient inputs. This process disrupts the balance of the marine food web, causes excessive reproduction of plankton and fluctuations in oxygen levels, and affects species diversity [2]. It should not be overlooked that, as it is a semi-enclosed system, it still carries the potential for change caused by human activity. In addition, it has been reported that the Black Sea is warming rapidly [11]. In the Black Sea, sea surface temperatures are rising significantly, leading to a decline in oxygen levels. These changes threaten the ecosystem's balance by reducing the habitat available for marine organisms [12]. Moreover, changes in the ecosystem also support the introduction of alien species [13]. This may lead to negative events that may occur immediately or later for local species.

Estimating what is happening now and what will happen in the future with climate change can help us understand how the environment is changing. This can let us think ahead about ways to stop problems before they happen, lower risks, and make long-term plans for managing the ecosystem. This study aims to assess the impact of climate change on the future distribution and habitat availability of commercial fish species in the Black Sea. By modeling their current suitable areas, it evaluates potential habitat shifts and losses these species may encounter in the coming years.

Materials and methods

Pre-processing and management

Based on field work conducted with purse seines, bottom and midwater trawls and gillnets between 2010 and 2023, 129, 187, 126, 147, and 136 spatial point data set was collected for anchovy (*Engraulis encrasicolus*), red mullet (*Mullus barbatus*), horse mackerel (*Trachurus trachurus*), turbot (*Scophthalmus maximus*), and whiting (*Merlangius merlangus*), respectively. In addition, the data set that have longitude and latitude for each species was taken from GBIF (https://doi.org/https://doi.org/10.15468/dl.ys9auw for anchovy; https://doi.org/https://doi.org/10.15468/dl.yby7gd for red mullet; https://doi.org/https://doi.org/10.15468/dl.shdxvx for whiting; https://doi.org/https://doi.org/10.15468/dl.p77k33 for turbot; https://doi.org/https://doi.org/10.15468/dl.jy7ypq for horse mackerel). All spatial point data sets were checked to see whether they include duplicate records or not using *spThin* package [14] in R [15] and duplicate records were removed (Fig. 1).

In present-day conditions (decade 2010–2020), all environmental variables, at the global scale, for surface conditions, at a spatial resolution of 0.05° were downloaded from Bio-ORACLE version 3.0 based on Shared Socioeconomic Pathway (SSP) scenarios based on a multi-model ensemble with data from CMIP6 [16]. A total of 17 variables as min, mean, max, and range were downloaded for this study (Table 1).

The study area was masked by the shape files belong to Black Sea and the Sea of Azov which were downloaded from Marine Regions [17]. This process was handled using spatial analysis in the toolbox of ArcMap v10.4.1. Thus, all global variables were masked for the study area and the variables were set to the same spatial extent and coordinate system in the ArcMap environment. In future conditions, two time periods were calibrated as decade 2030–2040 and 2090–2100. The conditions are based on two SSP scenarios of future climate change which are "sustainability" scenario SSP1–1.9 and the "fossil-fuelled development" SSP5–8.5 scenario. SSP1–1.9 is the scenario that envisions a significant reduction in carbon emissions by 2050, resulting in temperature stabilization at 1.8 °C and SSP5–8.5 is the scenario that envisions CO2 emissions are expected to escalate until 2050, leading to an average temperature increase of 4.4 °C To identify and eliminate collinear variables, the Variance Inflation Factor (VIF) [18] was calculated using the *usdm* package [19]. This method relies on the square of the multiple correlation coefficient (R^2) obtained from regression analysis. This process was undergone for each species independently, as it involves extracting the variables from species georeferences and subsequently computing correlation coefficients. Consequently, the most influential variables affecting species distribution were determined for each species. Thus, many variables were eliminated and the variables that will be used in the analysis were kept (Table 1).

Processing of the model

In our study of species distribution modeling, the *sdm* package was employed [20]. This package utilizes ensemble techniques to predict the spatial and temporal distribution patterns of species. Ensemble technique were performed random selection of points within study area as pseudo-absence/background data points [21]. The ensemble modeling approach incorporated five algorithms: Maxent (Maximum Entropy) [22], GLM (Generalized Linear Models) [23], SVM (Support Vector Machines) [24], Bioclim (Climate-Envelope-Model) [25], and RF (Random Forest) [26]. Maxent utilizes bioclimatic variables alongside species presence and background data to generate species distribution maps [27, 28]. GLM, on the other hand, assesses data using both presence and absence records [29]. SVM is proficient in simulating species presence and absence [30], while Bioclim

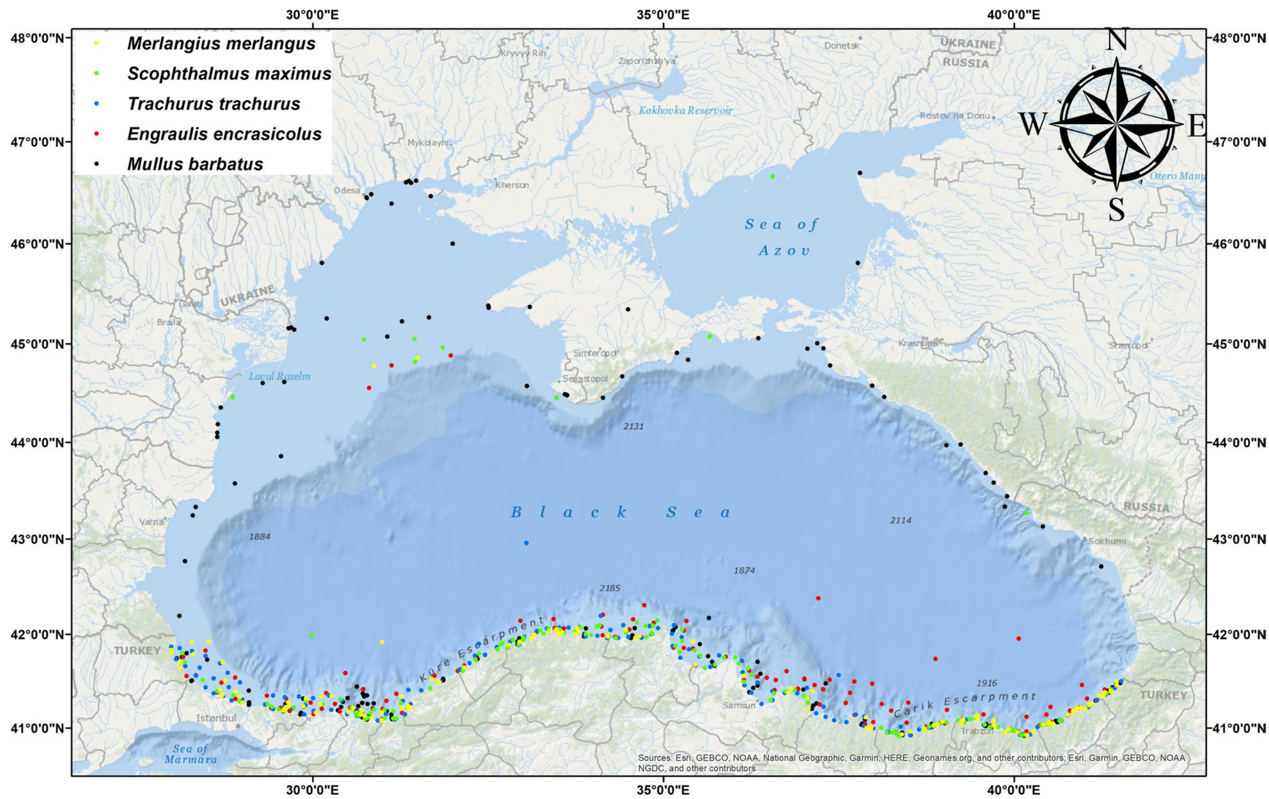

Fig. 1 Occurrence data of commercial fish species studied in the Black Sea

Table 1 List of layers downloaded for both present and future. Bolds indicate the variables that remain based on VIF measure

Variables	Units	Max	Mean	Min	Range
Ocean temperature	ºC	✓	✓	✓	✓
Salinity	–	✓	✓	✓	✔*****
Sea water velocity	$m.s^{-1}$	✓	✓	✓	✓
Sea water direction	Degree	✓	✔*****	✔*****	✔*****
Nitrate	$mmol. m^{-3}$	✔****	✓	✓	✔**
Phosphate	$mmol. m^{-3}$	✓	✓	✔**	✔*****
Silicate	$mmol. m^{-3}$	✓	✓	✓	✔***
Dissolved molecular oxygen	$mmol. m^{-3}$	✓	✓	✓	✓
Iron	$mmol. m^{-3}$	✓	✓	✓	✓
Primary productivity	$mmol. m^{-3}$	✓	✓	✔****	✓
pH	–	✓	✓	✓	✓
Chlorophyll	$mmol. m^{-3}$	✓	✓	✓	✔*****
Sea ice thickness	m	✓	✓	✓	✓
Sea ice cover	Fraction	✓	✓	✓	✓
Cloud cover	%	✓	✓	✓	✓
Mixed layer depth	m	✓	✓	✓	✔*****
Air temperature	ºC	✓	✓	✔*****	✓

Five stars represent variables common to all species, four stars to *T. mediterraneus*, *M. merlangus*, *E. encrasicolus*, and *S. maximus*, three stars to *M. merlangus*, *E. encrasicolus*, *M. barbatus*, and *S. maximus*, and two stars to *M. barbatus*

requires only species presence data [31]. RF operates on presence-only data along with background samples [32]. These diverse models, each employing distinct methodologies and techniques, represent some of the most effective approaches in species distribution modeling [20]. By incorporating these models into our analysis, the aim to reduce the inherent uncertainties associated with individual models, a strategy advocated by several previous studies [33, 34]. Moreover, from the model results run for each species, the importance of variables was calculated using the 'getVarImp' method.

Post-processing of the model

To construct the ensemble model, default parameters were adopted: 70% of the data for training and 30% for testing was allocated. Bootstrap was employed for data partitioning, with each method executed across 10 replicates to ensure robustness and reliability in our modeling approach. The "gRandom" method was applied to randomly generate records within the background space. As a result, 10,000 pseudo-absence records were created for each fish species. To assess the effectiveness of each model, two statistical methods were employed. First, the receiver operating characteristic (ROC) analysis was conducted, focusing on the area under the curve (AUC)

[35]. Second, the true skill statistic (TSS) was employed [36]. The AUC value varies between 0 and 1 [37]. A value nearing 1 suggests a clear discrimination between presence and pseudo-absence data, indicating a robust performance. Conversely, a value of 0.5 or lower signifies overlap between the data sets [38]. The TSS scale ranges from + 1 to − 1. A value closer to + 1 indicates excellent model performance, while a value below 0 suggests subpar performance [36]. According to multiple evaluation metrics, including the Area Under the Curve (AUC), True Skill Statistic (TSS), sensitivity, and specificity, Models with an AUC greater than 0.85 were classified as top performers, whereas those falling below this threshold were excluded. Binary presence/absence maps were then generated using the TSS as the threshold. In addition, to calculate habitat change between the present and future distribution, the mean threshold was evaluated using 'getEvaluation' method under sdm package. Negative means less suitability in the future compared to the present time, whereas positive means suitability is increased for species.

Results

The performance of model and variable importance

SDM of five commercial fish species ranged from good to excellent prediction performance. Anchovy had 0.95 AUC and 0.8 TSS score, and it showed the lowest TSS value. Red mullet exhibited a 0.96 score for AUC and 0.84 score for TSS. Horse mackerel, turbot, and whiting had the highest AUC and TSS scores, 0.96, 0.98, 0.97 for AUC and 0.87, 0.89, and 0.87 for TSS, respectively. When comparing SDM model performance of five commercial fish species, RF had generally the highest performance for AUC (Table 2).

Table 2 Model mean performance for each species, using test data set generated based on partitioning

Mullus barbatus				
	AUC	**COR**	**TSS**	**Deviance**
GLM	0.91	0.3	0.69	0.09
RF	0.96	0.64	0.84	0.06
MAXENT	0.94	0.33	0.77	0.29
BIOCLIM	0.75	0.17	0.49	0.3
SVM	0.89	0.26	0.69	0.1
Engraulis encrasicolus				
GLM	0.92	0.2	0.74	0.09
RF	0.95	0.53	0.8	0.07
MAXENT	0.93	0.26	0.79	0.34
BIOCLIM	0.71	0.15	0.43	0.26
SVM	0.88	0.19	0.64	0.1
Trachurus trachurus				
GLM	0.92	0.24	0.75	0.09
RF	0.96	0.49	0.85	0.07
MAXENT	0.96	0.31	0.87	0.24
BIOCLIM	0.69	0.12	0.38	0.32
SVM	0.92	0.18	0.75	0.1
Scophthalmus maximus				
GLM	0.93	0.32	0.75	0.09
RF	0.98	0.55	0.89	0.06
MAXENT	0.97	0.4	0.89	0.21
BIOCLIM	0.68	0.14	0.37	0.27
SVM	0.94	0.27	0.8	0.1
Merlangius merlangus				
GLM	0.93	0.26	0.76	0.08
RF	0.97	0.57	0.87	0.05
MAXENT	0.96	0.34	0.84	0.21
BIOCLIM	0.67	0.1	0.36	0.34
SVM	0.92	0.24	0.75	0.09

The most of variables were common for all species (Table 1). The performances on models of them were different. For red mullet, Silicate_range (22.1%) was the most dominant variable, following by Nitrate_range (16.4%), Phosphate_range (13.8%), Air_temperature_min (12.9%), and Phosphate_range (10.4%) (Fig. S1). In anchovy, Current_direction_min (26.5%), Silicate_range (19.3%), Phosphate_range (18.8%), Nitrate_max (17.3%), Chlorophyll_range (13.7%), Primary_productivity_min (12.3%), and Mixed_layer_depth_range (11.1%) were the most effective variables (Fig. S2). Nitrate_max (37.6%) between ten variables was the most important for horse mackerel. This variable was followed by Salinity_range (13.7%), Phosphate_range (11.9%), Current_direction_min (11.5%), Chlorophyll_range (11.3%), Current_direction_mean (10.4%), Primary_productivity_min (10.2%), and Air_temperature_min (10.1%) (Fig. S3). The variables that are relative importance for *turbot* were Silicate_range (25.2%), Current_direction_min (11.3%), Air_temperature_min (14.1%), and Primary_productivity_min (10.3%) (Fig. S4). For the distribution of whiting, Nitrate_max (30.2%) was the most obvious variable and others were Air_temperature_min (20.5%), Chlorophyll_range (19.6%), Current_direction_min (13.5%), Mixed_layer_depth_range (11.9%), and Primary_productivity_min (10.3%) (Fig. S5) (Table S1). Other all variables showed a score of 10% below for all species.

Present and future potential distribution of five commercial fish species under climate change

The ensemble model suggests that current distribution patterns are suitable areas for commercial species along the southern coast of the Black Sea. According to the model results, the suitability probability of occurrence value in the current distribution maps is generally 0.4–0.6, and it is understood that the Southern Black Sea

Coasts are moderately suitable areas. However, the same cannot be said for the results of future climate scenarios. While a decline in suitable habitats is generally observed for all commercial species, this negative trend is expected to be even more concerning, particularly for pelagic species, such as anchovy and horse mackerel.

In the SSP1–1.9 scenario, the suitable areas of red mullet decreased in the southeastern Black Sea in 2030–2040. In the same scenario, almost the entire Black Sea was at low suitability (0.2) for this species in 2090–2100. In the SSP5–8.5 scenario and in 2030–2040, the suitability of red mullet started to decrease along the coastal Black Sea, but in 2090–2100, suitable areas were formed in patches along the southern coast of the Black Sea, but these areas were not found in the southwestern coast (Fig. 2).

For anchovy, all scenarios of future predictions in different time periods were different from the present. For

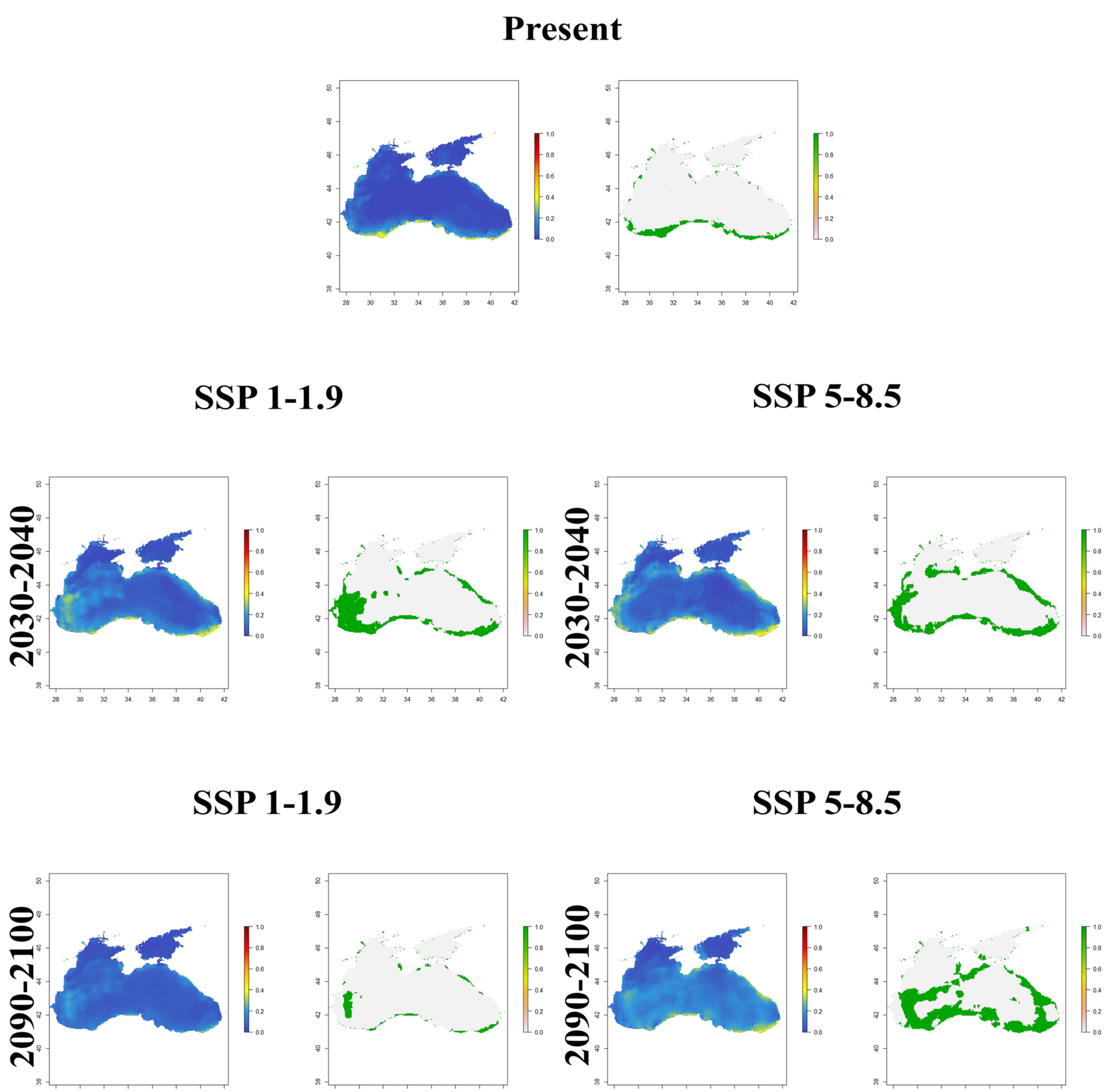

Fig. 2 Present and future patterns of red mullet under climate change. Warm colors present the most suitable habitats. In the binary map, green areas indicate the presence of the species

the most abundant fish of the Black Sea, all future scenarios pointed to a possible worst-case scenario, where suitable areas for anchovy were almost non-existent (Fig. 3).

A striking situation occurred for horse mackerel compared to the current distribution. All future scenario time periods showed similar distribution patterns. In 2030–2040, low suitability areas occurred in the southeastern Black Sea, while suitable areas disappeared completely in 2090–2100 (Fig. 4).

Areas suitable for *turbot* were observed to be in a decreasing trend both in all scenarios and time periods (Fig. 5).

In the SSP1–1.9 scenario, suitable areas for whiting appeared around the southwestern Black Sea and Crimea, while this suitability was still evident in the SSP5–8.5 scenario. However, in the SSP5–8.5 scenario and in the period 2090–2100, suitable areas for this species decreased considerably and, It is estimated that

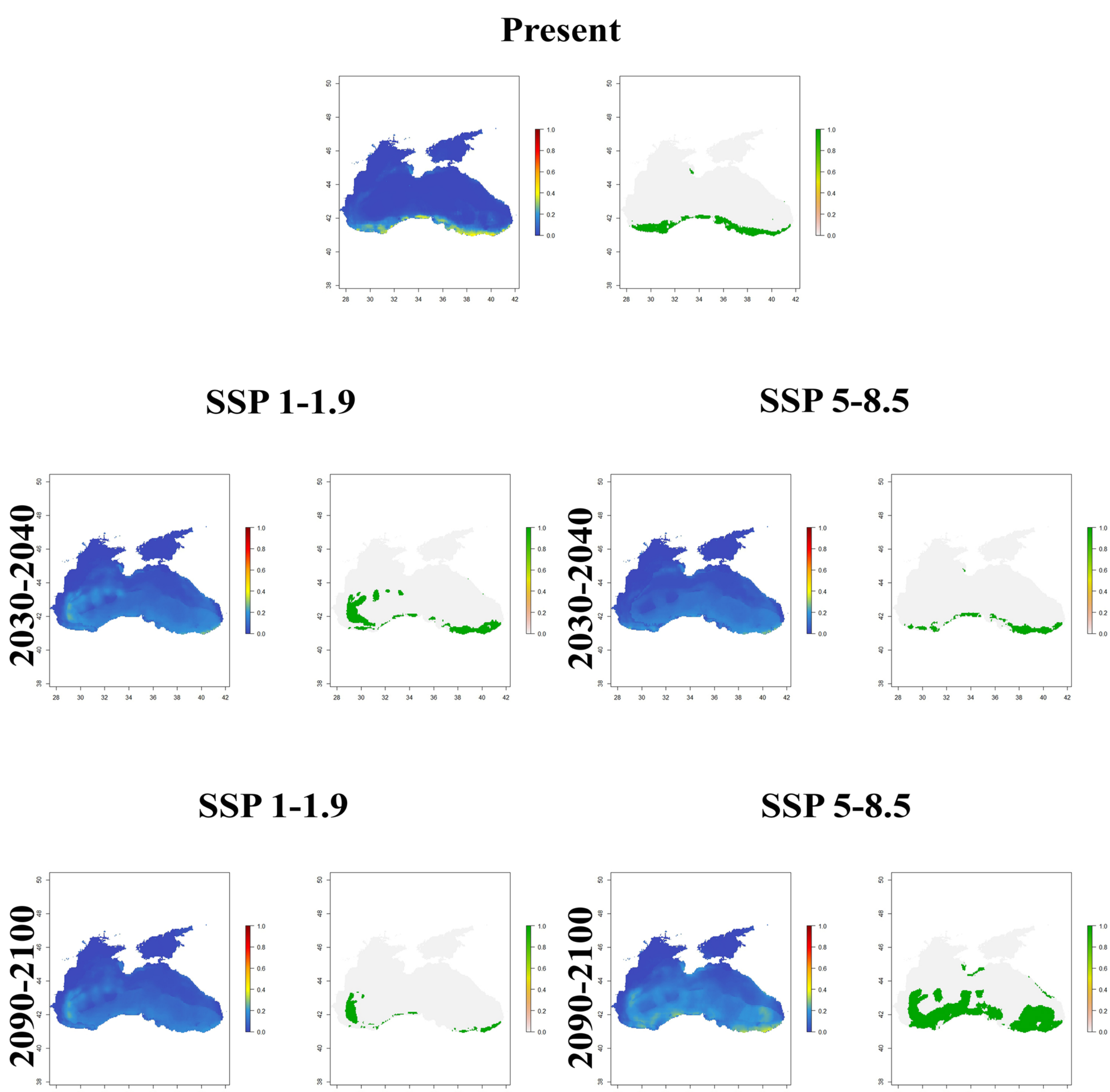

Fig. 3 Present and future patterns of anchovy under climate change. Warm colors present the most suitable habitats. In the binary map, green areas indicate the presence of the species

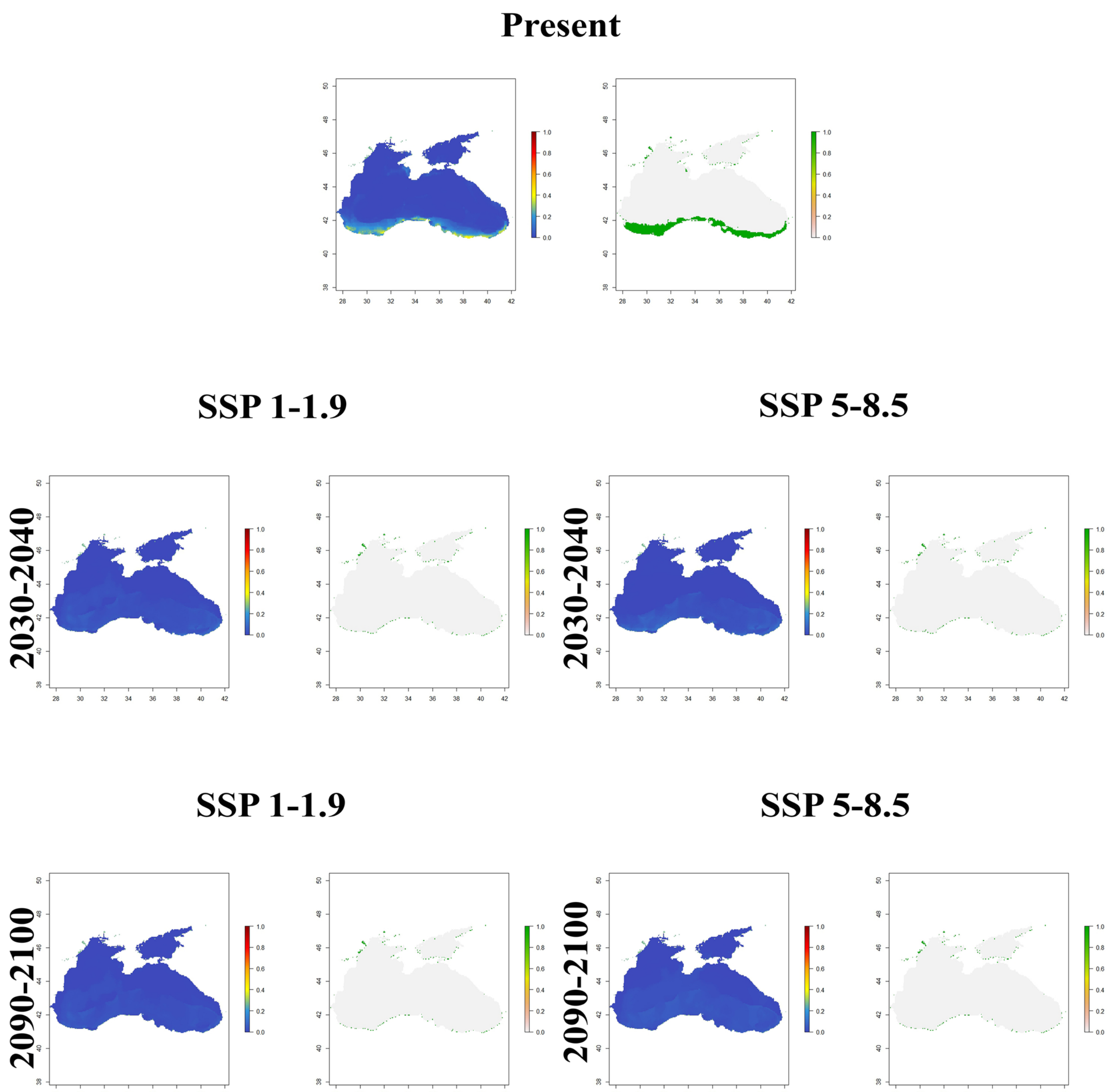

Fig. 4 Present and future patterns of horse mackerel under climate change. Warm colors present the most suitable habitats. In the binary map, green areas indicate the presence of the species

the probability of occurrence value of almost the entire Southern Black Sea will fall to 0.2 levels (Fig. 6).

Changes in the present and future climatic conditions for fish species

It is predicted that suitable habitats for red mullet will decrease in the southern parts of the Black Sea in all climate scenarios and time periods. However, in the 2030–2040-time period and SSP1–1.9 and 5–8.5 scenarios, the new low-scale habitats are in the areas in the west and northeast of the Black Sea. In the 2090–2100 projection of the SSP1–1.9 scenario, very small-scale suitable habitats have formed, especially on the west coast between latitudes 42°–43°, whereas in the SSP5-8.5 scenario, habitat shift has occurred only on the east coast between latitudes 42.5°N–43°N, and red mullet has retreated from all coastal areas (Fig. 7).

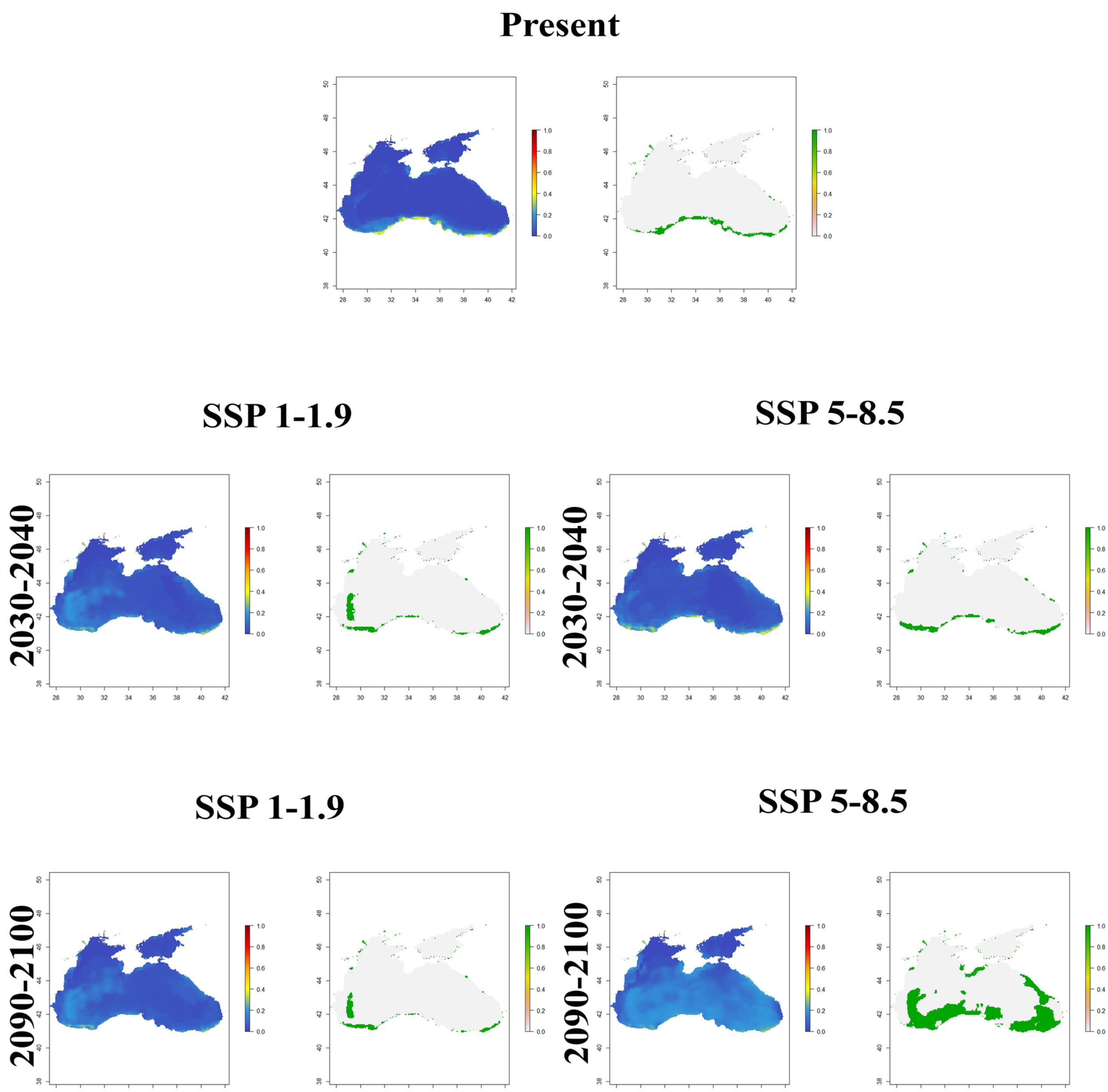

Fig. 5 Present and future patterns of turbot under climate change. Warm colors present the most suitable habitats. In the binary map, green areas indicate the presence of the species

SSP1–1.9 and 5–8.5 2030–2040 projections show significant losses in the southern coast, while low (probability of occurrence value 0.5) habitat shifting is seen in the northern coastal areas. Both scenarios show general habitat loss in the southern coast and widespread but very low-level habitat shifting in the northern coast in the 2090–2100-time period (Fig. 8). Habitats for anchovy are projected to become increasingly unsuitable and almost disappear along the southern coast of the Black Sea (Fig. 8).

High levels of habitat loss for horse mackerel are predicted in coastal areas of the Black Sea. Results are similar to anchovy in all climate scenarios. Almost the same rate of losses is observed in the moderately suitable areas (probability of occurrence value approximately 0.4) seen in the current distribution (Fig. 9).

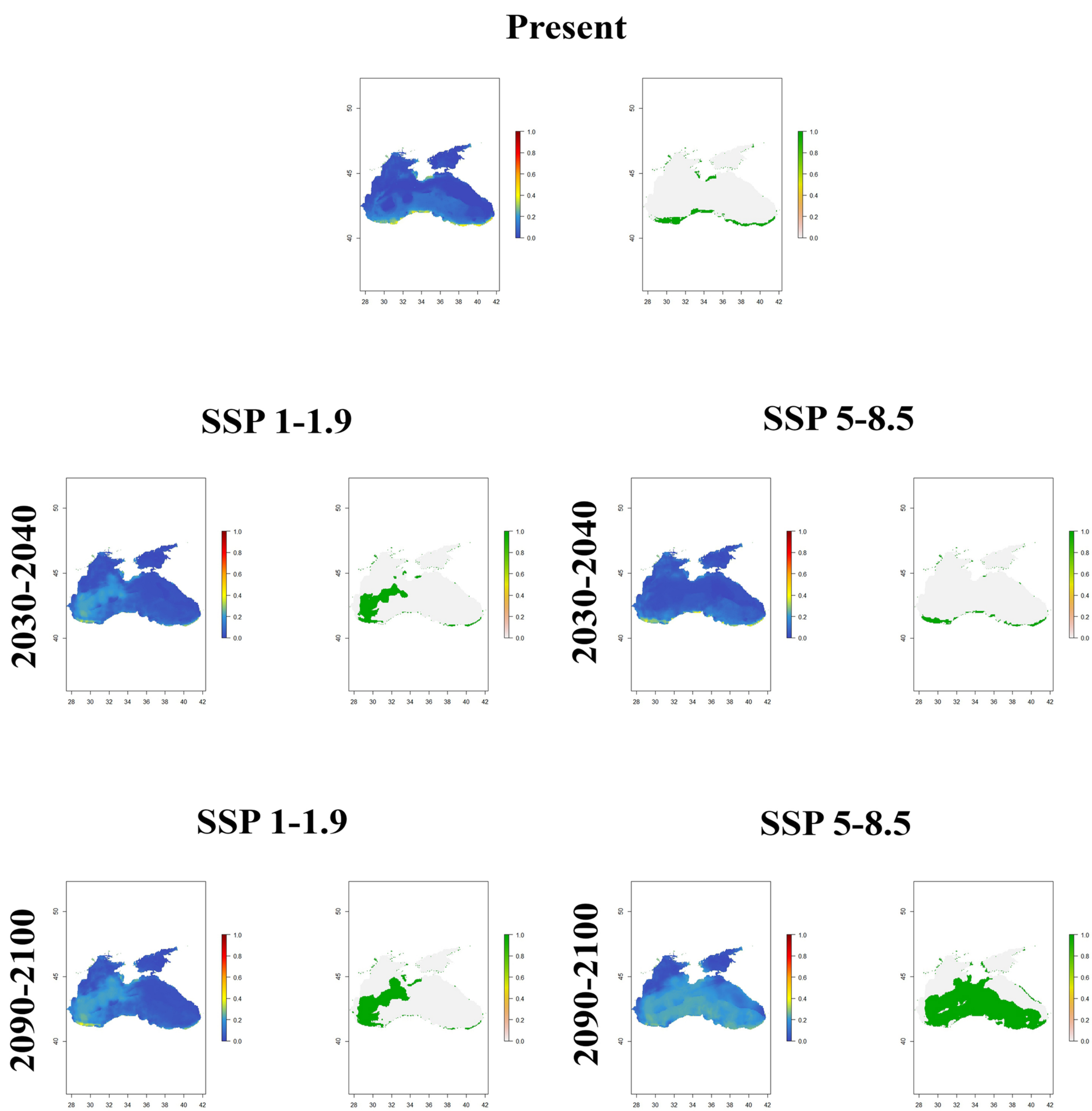

Fig. 6 Present and future patterns of whiting under climate change. Warm colors present the most suitable habitats. In the binary map, green areas indicate the presence of the species

In both scenarios, although northward shifts of 0.1–0.2 are planned for turbot in the 2030–2040 period, coastal negative impacts are predicted in the 2090–2100 projections. A noteworthy finding is that habitat shifts of approximately 0.2 are expected in the future along the Sochi coast (Fig. 10).

It is predicted that habitat losses for whiting will increase in the most coastal areas of the Black Sea, and there will be shifts toward deeper areas, especially in the 2090–2100 scenarios (Fig. 11). The bathymetry of the Black Sea is a subject that needs to be carefully considered. Especially the narrowness of the neritic zone in almost all of the Black Sea limits the habitats of the species.

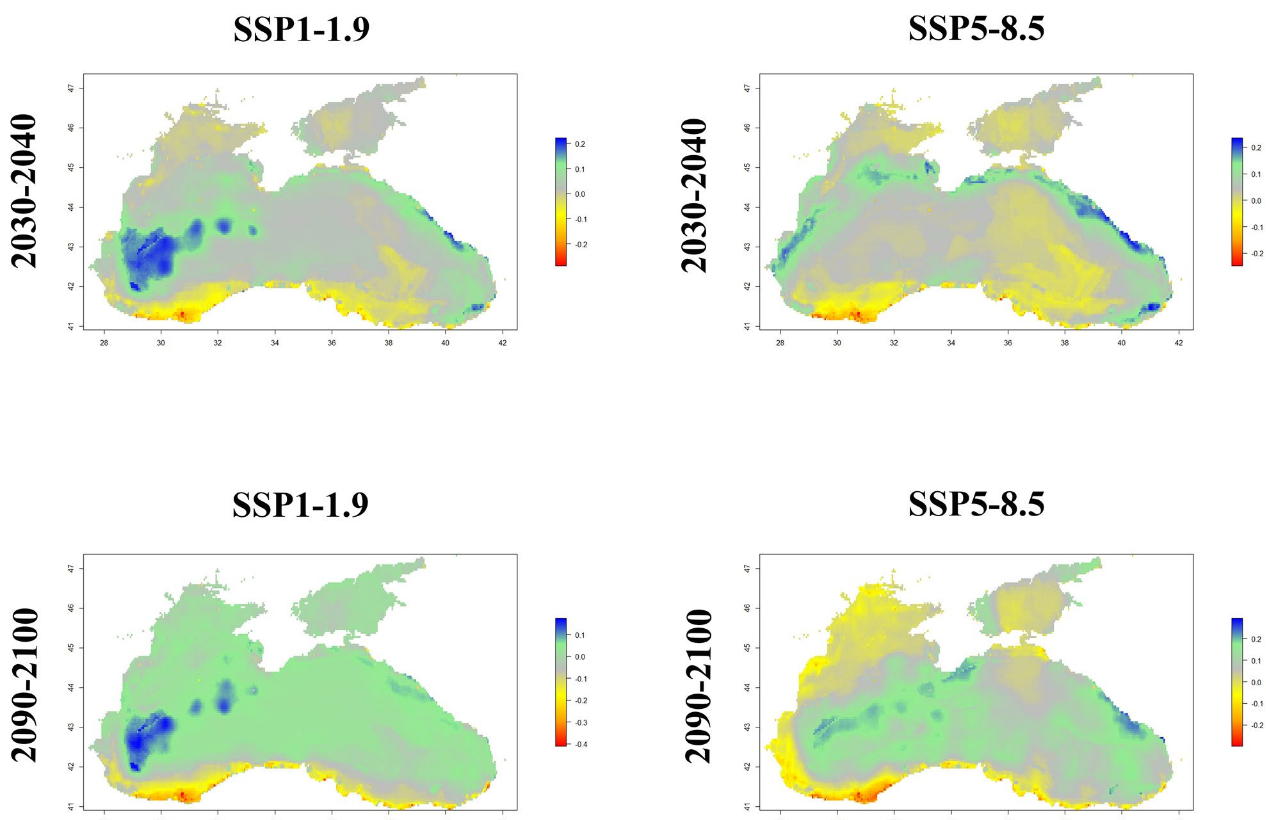

Fig. 7 Future predictions of red mullet. Negative value shows the suitability decline, while positive value indicates the suitability increase. Zero indicates no change the suitability

Discussion

It is claimed that the Black Sea is the most anthropogenically disturbed sea in the world, due to various reasons (pollution, overexploitation, climate change, etc.) [39]. This is one of the reasons why the annual landings of commercial fish tend to fluctuate in a downward trend [40]. However, it is now necessary to consider habitat destruction or loss due to climate change. The present study predicts future distribution and habitat losses of five commercial fish under the influence of climate change. The findings show a widespread pattern of habitat degradation and distribution changes for all commercial fish species in the Black Sea under possible climate scenarios. Some species show significant losses of suitable habitat (e.g., anchovy and horse mackerel), while others show a steady decline with possible displacement to new areas. The expected changes will not be limited to one country but will affect fisheries and marine biodiversity in the entire Black Sea region. The observed northward and offshore migrations of many species should be taken into account, as rising water temperatures and changing oceanographic conditions may transform fisheries dynamics, as well as affect traditional consumption preferences and fisheries economics.

When comparing the current distribution and climate scenarios of red mullet, it is observed that the suitability values in the southern coasts will decrease. In future projections, suitable habitats with lower values than current distribution are expected to appear in other parts of the Black Sea (Fig. 2). Habitat losses are predicted to occur along the southern coast under both climate scenarios (Fig. 7). Both climate scenarios present a very important habitat loss for red mullet over the next hundred years, posing a very risky situation for its sustainability in the Black Sea. In addition, there are several previously mentioned observations, including decreases in average lengths, length frequencies, and maximum age data obtained from biological studies on red mullet. This means the health of the stock is starting to deteriorate, and scientists have attributed this to overfishing and human-caused pollutants [41–44]. It is expected that the decrease in fish size under the influence of climate change will vary from species to species. A reduction in size is anticipated, particularly among smaller species [45]. It has been reported that red mullet fish have shrunk

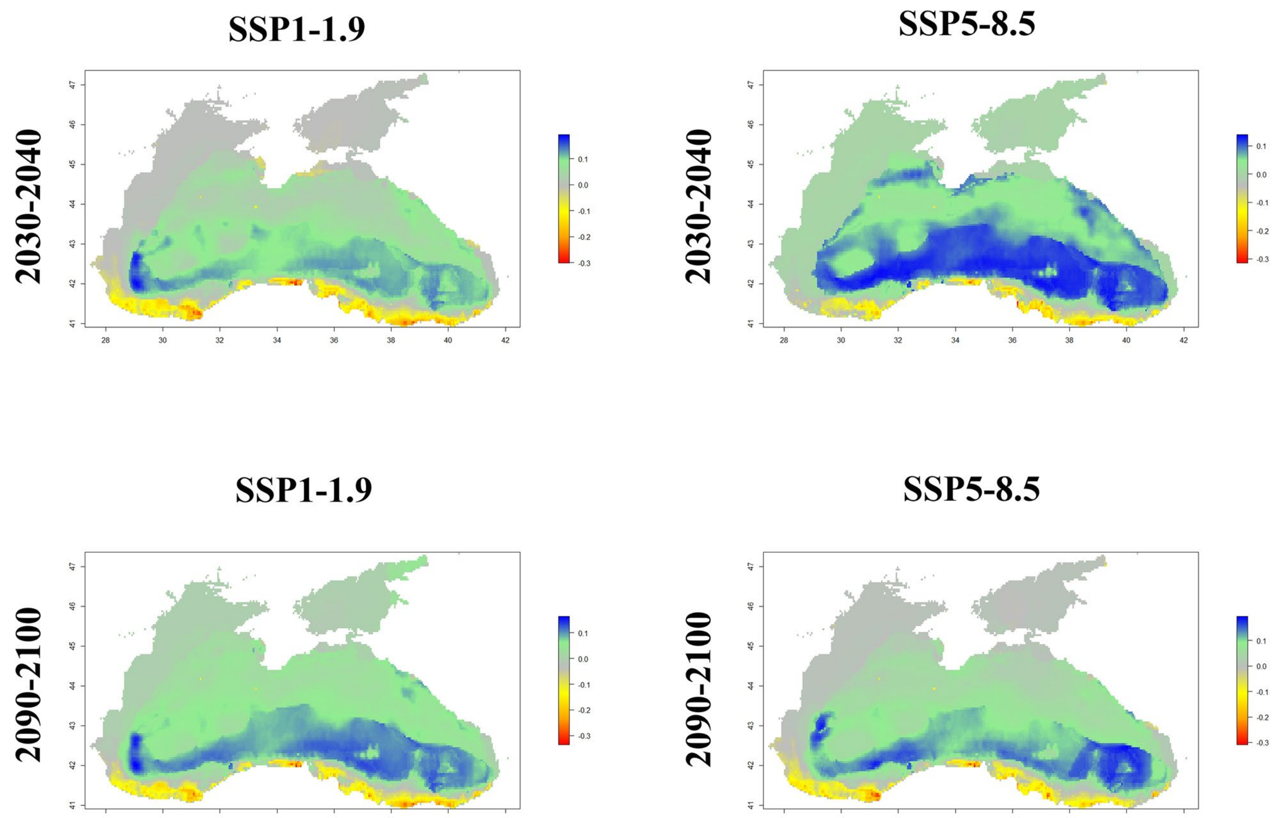

Fig. 8 Future predictions of anchovy. Negative value shows the suitability decline, while positive value indicates the suitability increase. Zero indicates no change the suitability

in size on the Georgian coast (only 0.3% of red mullet production from the Black Sea is obtained by Georgia) and that this situation may be due to fishing pressure [46]. It is obvious that these negative developments, especially observed on the coasts, where a much smaller fleet is operated compared to Türkiye, cannot be explained only by fishing pressure. This suggests that additional factors, such as environmental changes, habitat degradation, or climate-related influences, may also play a role in this phenomenon and should be further investigated.

When examining the current distribution map, a more pessimistic outcome emerges for anchovy (Fig. 3). The probability of occurrence value of suitable areas is 0.4, indicating that the southern coast of the Black Sea is going to close to being unsuitable habitat for anchovy. Anchovy account for most of the annual production in the Black Sea and fluctuations in its production have been linked to ecosystem changes (eutrophication), the introduction of invasive species (jellyfish), and overfishing [2, 47]. In addition, while it was previously understood that only the northern coasts functioned as spawning areas, ichthyoplankton surveys conducted on the southern coasts of the Black Sea after the 90 s revealed the presence of anchovy eggs, with their abundance gradually increasing. Researchers interpreted this difference as an indication that the spawning areas for anchovy may have changed due to alterations in the ecosystem. Furthermore, some of the negative impacts have disappeared compared to the past, settlement spawning stocks have been mentioned along the southern coast [48]. Considering all this information and this study model results, it can be inferred that the priority spawning areas for anchovy stocks have decreased, suggesting that virtually any area in the Black Sea could be a spawning area. This change in priority spawning areas indicates a potential disruption in the anchovy's reproductive dynamics, which could negatively impact stock sustainability and long-term fishery yields in the Black Sea.

Recent studies on anchovy fishery indicate that catch amounts in Bulgaria and Romania have not reached levels observed in previous periods, which may signal a change in migration routes [49]. In addition, Chashchin et al. noted an increase in anchovy density along the Crimean coast during the warm winter of 2005 [50]. This situation is interpreted as anchovy migration linked to temperature, with the decline in catches on the southern coasts

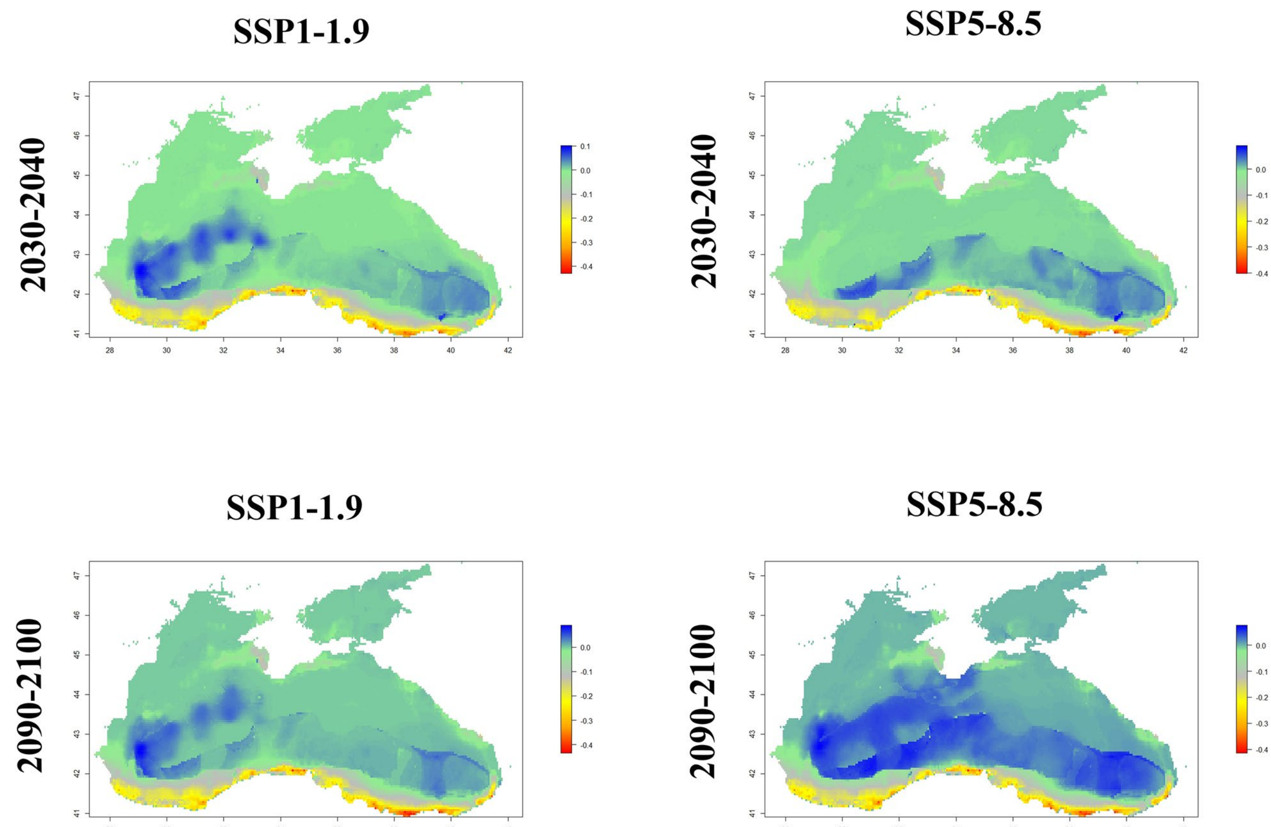

Fig. 9 Future predictions of horse mackerel. Negative value shows the suitability decline, while positive value indicates the suitability increase. Zero indicates no change the suitability

that year attributed to the warm winters experienced on the northern coasts [51]. In addition, unusual situations regarding migration, spawning grounds, and a downward trend in annual production that contradict previous information should be considered a warning for anchovy populations. Akkuş and Gucu also noted that the first maturity size of anchovy has decreased, which is likely to have negative effects on spawning stock biomass and recruitment [52]. They attributed these adverse changes to rising temperatures. Both the literature and our results confirm that the effects of climate change on the current distribution of anchovy are becoming increasingly evident. In all future projections, this situation becomes even worse.

Fisheries shift toward exploiting smaller fish after the large predatory fish at the top of the food chain are depleted. Many species that could be considered large predators have disappeared from the Black Sea over time [53]. For this reason, the behavior of fishermen in the Black Sea has also changed. Whiting was not commercially popular before the 1990s, and sprat has recently been used in fish meal processing so that have been subjected to fishing pressure that was not present before. Stocks of small pelagics are very important feeding supplies for other species. Therefore, it is possible that a decline in the abundance of small fish such as anchovy and sprat would also lead to the extinction of other fish that feed on this species [54–56]. Thus, it becomes evident that the Black Sea is caught in a vicious cycle that continuously disrupts the ecosystem and food chain. Because of their ecological significance, special attention should be given to small pelagics, and their fishing should always be managed.

Both the low suitability probability of occurrence value values in the current predicted distribution map and the nearly complete absence of suitable habitats in future projections indicate a concerning outcome for horse mackerel. It has been reported that the first maturity size of horse mackerel in the Black Sea has decreased and they have gained the ability to reproduce at smaller sizes. This situation is thought to be due to high fishing mortality and exploitation rates [57]. Alterations in oxygen levels and temperature resulting from climate change will influence fish metabolism, indicating a projected decrease in fish size as lower oxygen and high temperatures elevate energy demands [58]. For this reason, the reduction in

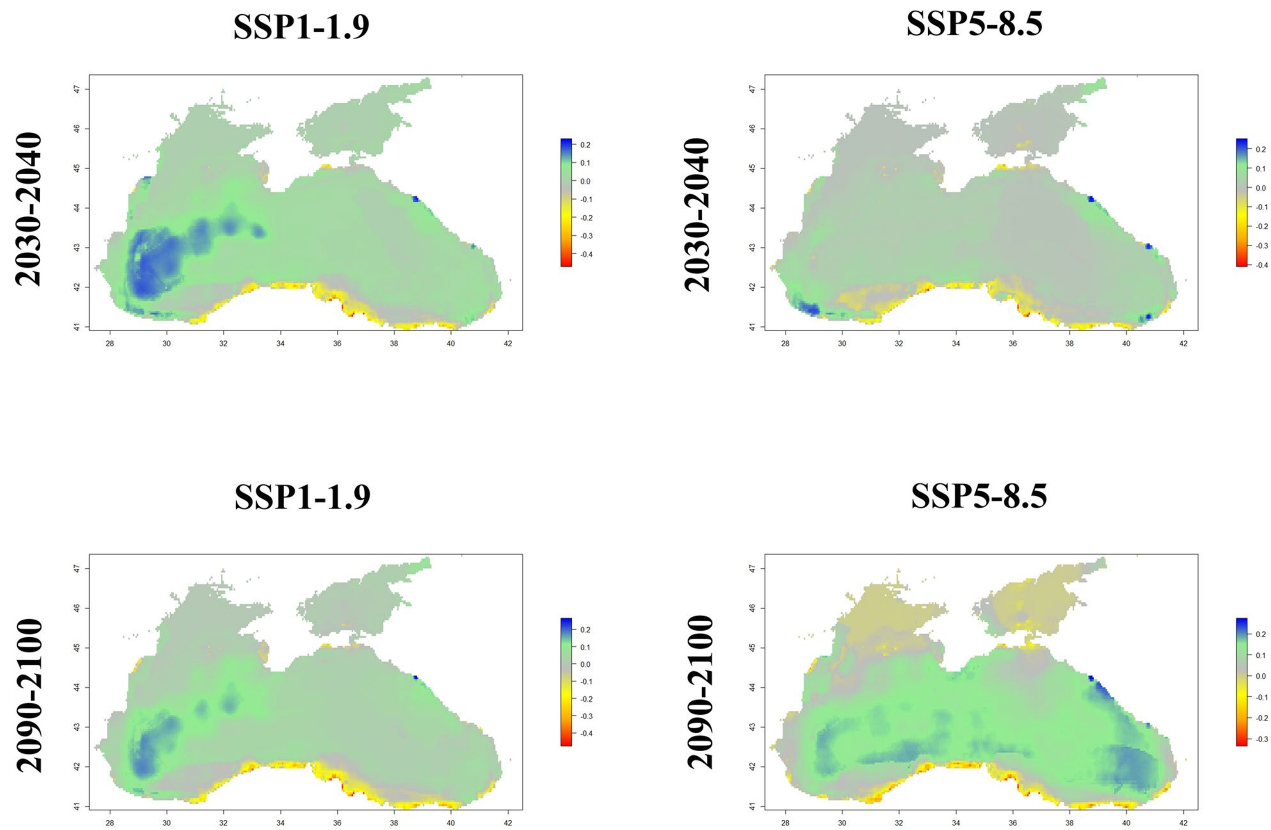

Fig. 10 Future predictions of turbot. Negative value shows the suitability decline, while positive value indicates the suitability increase. Zero indicates no change the suitability

horse mackerel sizes can also be attributed to climate change. Several morphological and genetic studies on horse mackerel in the Black Sea were conducted. Bektaş and Beldüz (2008) suggest that the Black Sea stock does not exhibit genetic differences and is genetically homogeneous [59]. However, another study, which examined otoliths and fish morphology in detail, reported the presence of distinct stocks in the Black Sea. It is particularly thought that otolith asymmetries may be linked to factors, such as habitat deterioration and stress [60]. When these studies are evaluated (despite the absence of genetic differences the association of morphological differences with habitat changes and stress, and the decreasing fish length), it may indicate that the effects of climate change are becoming apparent earlier.

The demersal fish species with the highest commercial value in the Black Sea is the turbot. When the production amounts of both Türkiye and the countries bordering the Black Sea are examined over the years, it is seen that there is a continuous downward trend [4]. When the distribution areas are examined on the native distribution map, the highest relative probabilities of occurrence values are the north-eastern coasts of the Atlantic Ocean and the Black Sea [61]. Giragosov and Khanaychenko mentioned some negative aspects of turbot stocks in their long-term data-based studies [62]. In particular, the male–female ratio was very low and this situation reduced reproductive success by up to 5 times compared to the past and the average lengths of females and males were different. They emphasized that changes in zooplankton abundance and diversity and abnormal microalgae blooms can negatively affect the larval development and survival rates of turbot fry and that this situation is caused by overfishing and anthropogenic pollutants. The northwestern continental shelf has seen an improvement in production and the prevention of illegal fishing in recent years [63]. In fact, this improvement may be an artificial one reflected in the figures. The rise in landings in countries such as Ukraine, Bulgaria, and Romania might be attributed to their increased focus on this species due to imports into the European Union, their increased fishing capacity, and illegal fishing activities have been prevented in this region. However, it is noteworthy that the total annual catch of the Black sea has not reached the figures of the early 1980s or 2000 [4, 5, 64]. Moreover, on

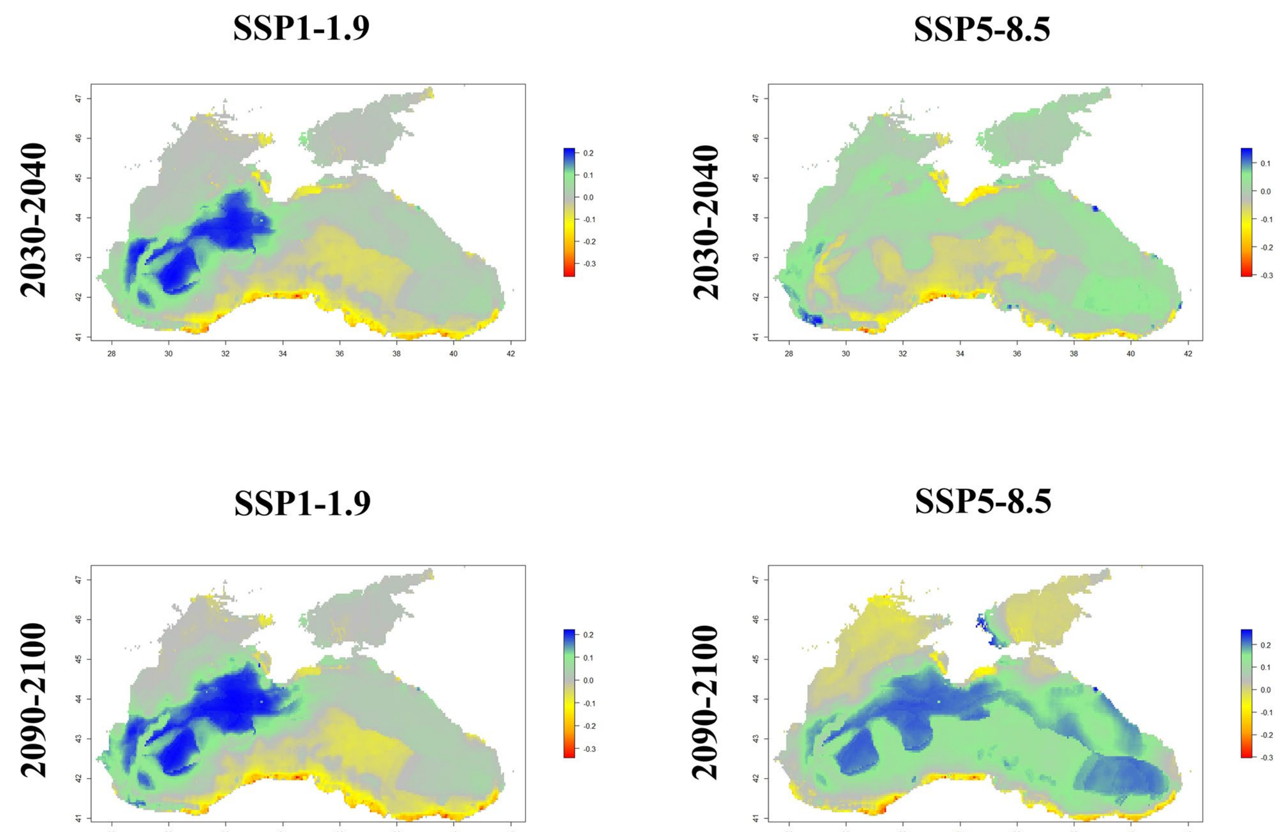

Fig. 11 Future predictions of whiting. Negative value shows the suitability decline, while positive value indicates the suitability increase. Zero indicates no change the suitability

the Bulgarian coast, low haplotype and nucleoid diversity of turbot in some areas has been considered as a sign of stock collapse or a bottleneck, and as in our results, habitat losses are also mentioned on the northern coast of Bulgaria [65]. The fact that similar results are predicted in both countries, along with the previously mentioned negative aspects, should be considered evidence that we are facing a climate change issue that requires careful attention, particularly for turbot.

Whiting was the dominant benthic fish caught in the Black Sea; however, its annual yield declined significantly after the 1990s [66, 67]. Moreover, different results can be obtained in fish biology studies depending on the sampling procedure [68], here is a general situation for the whiting stocks of the Black Sea, which is that the average sizes tend to decrease compared to the past [69]. A study of whiting populations in Türkiye revealed substantial haplotype diversity and little nucleotide diversity [70]. This circumstance may be elucidated as a rapid population surge following a recent bottleneck in the whiting population [71]. The landing of whiting in the Black Sea, reached 20,000 tonnes in 1998, dropped to its one-quarter and approximately 7000 tones in 2005 [72]. Although annual production has occasionally exceeded 10,000 tonnes after 2005, the figures of the pre-2000s have never been reached again. Whiting can reproduce all year round, although their reproductive activities decrease in the summer [66]. Therefore, after a population collapse, this species has the potential to recover more quickly than other commercial species in the Black Sea. For this reason, whiting should be expected as one of the commercial species best able to cope with future climate change impacts, both because of its preference for deeper waters and its reproduction activities continue throughout the year. As a matter of fact, our findings are consistent with this statement. When future patterns and habitat loss maps are examined, whiting has higher scores for suitable areas than other commercial species of the Black Sea in both scenarios.

Perhaps fish in the Black Sea may be able to withstand temperature changes; however, the real question that is thought-provoking is their ability to cope with the deterioration of food abundance and water quality. The model results indicate that environmental variables related to food and water quality, such as silicate, phosphate, nitrate, and primary productivity, play a crucial role in determining suitable habitats.

The region between 42.5°N and 44°N latitudes in the east of the Black Sea is remarkable according to our analysis results. When the habitat shift maps of demersal species are examined, there is a slight movement toward this region. This indicates that this region has the potential to be an important marine area and should be protected for the future.

The observed changes in the physical oceanography and eutrophication of the Black Sea are the result of natural and anthropogenic factors. The consequences of such events have been faced severely in the Black Sea in the past. Despite the intense interest in this topic, an international management plan should be advocated to manage and improve the health of this ecosystem due to adverse factors, such as climate change and ongoing nutrient inputs [39, 73, 74].

Climate change directly affects ecosystems and species, as increases in seawater temperature cause organisms to migrate toward polar latitudes [75, 76]. However, this may not be the case for species living in the Black Sea, as it has no connection to another marine system to the north. This situation may force local species to become trapped in the Black Sea and struggle to continue their life cycles in adverse conditions. Another problem will be the expansion invasion of areas in northern latitudes due to warming. Because the distribution areas of algae, invertebrates, and fish in warm seas are expanding [77, 78]. The introduction of Mediterranean-based or other species to the Black Sea could lead to both increased food competition and prey–predator relationships, thus increasing the pressure on native species of the Black Sea.

This study reveals that important commercial fish species in the Black Sea are under serious threat in the long term due to climate change. The preferred Bio-ORACLE v3.0 data set provides a holistic approach in terms of comparability and model consistency under both current and future conditions, as it provides climate projections with high spatial resolution and temporal dimension for the Black Sea. Model results are consistent with existing biological observations of habitat suitability reduction, distribution areas shrinking, declining stocks, changing spawning areas and migration routes. On the other hand, inconsistencies between the "unsuitable" areas predicted by the model in some regions and known species occurrences indicate the effects of factors such as data resolution, environmental variable selection and ecological tolerances of species on model performance. These differences do not indicate the deficiencies of the model, but rather the need for more integrated and flexible approaches in a unique marine system such as the Black Sea, which is semi-enclosed, has a persistent hydrogen sulfide layer at depth and is subject to intense anthropogenic impact.

Considering all these, the priority should be to reduce dynamic and complex anthropogenic effects [79]. The main way to cope with this situation is to develop reformist approaches in terms of fisheries management to gain time against climate change and to reduce the pressure on commercial species. Reducing fishing pressure can contribute to the survival of commercial species [80]. The spread of pollutants in the marine environment causes instability, disorder, harm or discomfort to fish [80]. For this reason, when implementing precautionary measures, not only the countries bordering the Black Sea but also all nations that contribute to its pollution by discharging waste through rivers must develop a comprehensive strategy. Moreover, climate change is a global problem and continuous monitoring and development of advanced modeling techniques are essential to improve predictions and guide management strategies. Addressing the climate problem of the Black Sea will be crucial to ensuring the long-term sustainability of fish stocks and the livelihoods of communities' dependent on its ecosystem. It is clear that if it continues in this way, it will have socio-economic effects as well as biological effects. The Black sea inhabitants will witness the disappearance of cheap and high-quality protein sources and communities that make their living from fishing.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-025-01147-0.

Supplementary Material 1.

Author contributions

SK.: methodology, formal analysis, visualization, writing-original draft. YC.: conceptualization, investigation, methodology, formal analysis, supervision, writing-original draft. GD.: investigation, writing-original draft.

Funding

This study has been supported by the Recep Tayyip Erdogan University Development Foundation (Grant number: 02025001021251).

Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 24 January 2025 Accepted: 7 June 2025
Published online: 18 June 2025

References

1. Zaitsev Y, Mamaev V (1997) Marine biological diversity in the Black Sea: a study of change and decline. GEF Black Sea Environmental Programme, United Nations Publications, New York, p 208
2. Bat L, Şahin F, Satılmış HH, Üstün F, Birinci-Özdemir Z, Kıdeyş AE, Shulman GE (2007) The changed ecosystem of the Black Sea and its impact on anchovy fisheries. J Fish Sci 1(4):191–227. https://doi.org/10.3153/jfscom.2007024
3. FAO (2024) The state of world fisheries and aquaculture 2024: blue transformation in action. FAO, Rome
4. Fisheries Statistics Query. Global capture production data. https://www.fao.org/fishery/statistics-query/en/gfcm_capture/gfcm_capture_quantity. Accessed 29 Nov 2024
5. Turkish Statistical Institute. https://biruni.tuik.gov.tr/medas/?kn=97&locale=tr. Accessed 29 Nov 2024
6. Yıldız T, Ulman A (2020) Analyzing gaps in policy: evaluation of the effectiveness of minimum landing sizes (MLS) regulations in Turkey. Mar Policy 115:103829. https://doi.org/10.1016/j.marpol.2020.103829
7. Ceylan Y, Şahin C (2019) Selectivity of different alternative cod ends and radial square mesh escape panels (RSEP). Turk J Fish Aquat Sci 19:451–461. https://doi.org/10.4194/1303-2712-v19_6_01
8. Kennelly SJ, Broadhurst MK (2021) A review of bycatch reduction in demersal fish trawls. Rev Fish Biol Fish 31:289–318. https://doi.org/10.1007/s11160-021-09644-0
9. Eigaard OR, Marchal P, Gislason H, Rijnsdorp AD (2014) Technological development and fisheries management. Rev Fish Sci Aquac 22(2):156–174. https://doi.org/10.1080/23308249.2014.899557
10. Oguz T, Dippner JW, Kaymaz Z (2006) Climatic regulation of the Black Sea hydro-meteorological and ecological properties at interannual-to-decadal time scales. J Mar Syst 60(3–4):235–254
11. Lima L, Ciliberti SA, Aydoğdu A, Masina S, Escudier R, Cipollone A et al (2021) Climate signals in the Black Sea from a multidecadal eddy-resolving reanalysis. Front Mar Sci 8:710973. https://doi.org/10.3389/fmars.2021.710973
12. Mohamed B, Ibrahim O, Nagy H (2022) Sea surface temperature variability and marine heatwaves in the Black Sea. Environ Sci Eur 34:2383. https://doi.org/10.3390/rs14102383
13. Dukes JS, Mooney HA (1999) Does global change increase the success of biological invaders? Trends Ecol Evol 14(4):135–139
14. Aiello-Lammens ME, Boria RA, Radosavljevic A, Vilela B, Anderson RP (2015) spThin: an R package for spatial thinning of species occurrence records for use in ecological niche models. Ecography 38(5):541–545. https://doi.org/10.1111/ecog.01132
15. R Core Team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/
16. Assis J, FernándezBejarano SJ, Salazar VW, Schepers L, Gouvêa L, Fragkopoulou E, Leclercq F, Vanhoorne B, Tyberghein L, Serrão EA, Verbruggen H, De Clerck O (2024) Bio-ORACLE v3.0: pushing marine data layers to the CMIP6 earth system models of climate change research. Glob Ecol Biogeogr 33:e13813
17. Flanders Marine Institute (2018) IHO sea areas, version 3. https://www.marineregions.org/. https://doi.org/10.14284/323
18. Marquardt DW (1970) Generalized inverses, ridge regression, biased linear estimation, and nonlinear estimation. Technometrics 12(3):591–612. https://doi.org/10.2307/1267205
19. Naimi B, Hamm NA, Groen TA, Skidmore AK, Toxopeus AG (2014) Where is positional uncertainty a problem for species distribution modelling? Ecography 37(2):191–203. https://doi.org/10.1111/j.1600-0587.2013.00205.x
20. Naimi B, Araújo MB (2016) Sdm: a reproducible and extensible R platform for species distribution modelling. Ecography 39(4):368–375. https://doi.org/10.1111/ecog.01881
21. Fielding AH, Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ Conserv 24:38–49
22. Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecol Model 190(3–4):231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026
23. McCullagh P, Nelder JA (1989) Generalized linear models, Monogr Stat Appl Probab, 2nd edn, vol 37. Chapman and Hall: London
24. Vapnik V (1995) The nature of statistical learning theory. Springer. https://doi.org/10.1007/978-1-4757-2440-0
25. Busby JR (1991) BIOCLIM—a bioclimate analysis and prediction system. Plant Prot Q 6:8–15
26. Breiman L (2001) Random forests. Mach Learn 45(1):5–32. https://doi.org/10.1023/A:1010933404324
27. Phillips SJ, Dudík M, Anderson RP, Schapire RE, Blair ME (2017) Opening the black box: an open-source release of Maxent. Ecography 40(7):887–893. https://doi.org/10.1111/ecog.03049
28. Phillips SJ, Dudík M, Schapire RE (2023) Maxent software for modeling species niches and distributions (version 3.4.1). http://biodiversityinformatics.amnh.org/open_source/maxent/. Accessed 11 10 2023
29. Carlos-Júnior LA, Creed JC, Marrs R, Lewis RJ, Moulton TP, Feijó-Lima R, Spencer M (2020) Generalized linear models outperform commonly used canonical analysis in estimating spatial structure of presence/absence data. PeerJ 8:e9777. https://doi.org/10.7717/peerj.9777
30. Drake JM, Randin C, Guisan A (2006) Modelling ecological niches with support vector machines. J Appl Ecol 43(3):424–432. https://doi.org/10.1111/j.1365-2664.2006.01141.x
31. Grimmett L, Whitsed R, Horta A (2020) Presence-only species distribution models are sensitive to sample prevalence: Evaluating models using spatial prediction stability and accuracy metrics. Ecol Model 431:109194. https://doi.org/10.1016/j.ecolmodel.2020.109194
32. Valavi R, Elith J, Lahoz-Monfort JJ, Guillera-Arroita G (2021) Modelling species presence-only data with random forests. Ecography 44(12):1731–1742. https://doi.org/10.1111/ecog.06238
33. Gómez D, Salvador P, Sanz J, Casanova C, Taratiel D, Casanova JL (2018) Machine learning approach to locate desert locust breeding areas based on ESA CCI soil moisture. J Appl Remote Sens 12(3):1. https://doi.org/10.1117/1.JRS.12.036007
34. Elias WC, Sintayehu DW, Arbo BF, Hadera AK (2022) Modelling the distribution of *Oxytenanthera abyssinica* (A. Richard) under changing climate: Implications for future dryland ecosystem restoration. Heliyon 24:e10393. https://doi.org/10.1016/j.heliyon.2022.e10393
35. Lobo JM, Jiménez-Valverde A, Real R (2008) AUC: a misleading measure of the performance of predictive distribution models. Glob Ecol Biogeogr 17(2):145–151. https://doi.org/10.1111/j.1466-8238.2007.00358.x
36. Allouche O, Tsoar A, Kadmon R (2006) Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). J Appl Ecol 43(6):1223–1232. https://doi.org/10.1111/j.1365-2664.2006.01214.x
37. Barbet-Massin M, Jiguet F, Albert CH, Thuiller W (2012) Selecting pseudo-absences for species distribution models: how, where and how many? Method Ecol Evol 3(2):327–338
38. Amaral IS, Bandeira Pereira J, Vancine MH, Morales AE, Althoff SL, Gregorin R, Pereira MJR, Valiati VH, Rosa de Oliveira L (2023) Where do they live? Predictive geographic distribution of *Tadarida brasiliensis brasiliensis* (Chiroptera, Molossidae) in South America. Neotrop Biol Conserv 18(3):139–156
39. Akoğlu E (2023) Ecological indicators reveal historical regime shifts in the Black Sea ecosystem. PeerJ 11:e11088. https://doi.org/10.7717/peerj.2023.11088
40. Demirel N, Zengin M, Ulman A (2020) First large-scale eastern Mediterranean and Black Sea stock assessment reveals a dramatic decline. Front Mar Sci 7:103. https://doi.org/10.3389/fmars.2020.00103
41. Aksu H, Erdem Y, Özdemir S, Erdem E (2011) Estimation of some population parameters of red mullet (*Mullus ponticus*, Essipov, 1927) caught in the Black Sea. J Fish Sci 5(4):345–353
42. Aydın M, Karadurmuş U (2013) An investigation on age, growth, and biological characteristics of red mullet (*Mullus barbatus* ponticus, Essipov, 1927) in the Eastern Black Sea. Iran J Fish Sci 12(2):277–288
43. Onay H, Dalgiç G, Ceylan Y (2023) Spatio-temporal distribution and population dynamics of the red mullet (*Mullus barbatus* Linnaeus, 1758) from the southeast Black Sea. J Anatol Environ Anim Sci 8(4):720–727
44. Yıldız T, Karakulak FS (2016) An investigation of age growth and mortality of the red mullet *Mullus barbatus* Linnaeus 1758 in the western Black Sea. Cah Biol Mar, 57: 415–425
45. Audzijonyte A, Richards SA, Stuart-Smith RD et al (2020) Fish body sizes change with temperature but not all species shrink with warming. Nat Ecol Evol 4:809–814. https://doi.org/10.1038/s41559-020-1171-0

46. Mikeladze R, Makharadze G, Joglidze T, Vadachkoria P, Salukvadze L, Leonchyk Y, Snigirov S (2023) Red mullet (*Mullus barbatus* ponticus Essipov, 1927) stock exploitation in Georgian coastal waters (2019–2021). Turk J Fish Aquat Sci. https://doi.org/10.4194/TRJFAS22461
47. Oguz T, Salihoğlu B, Fach B (2008) A coupled plankton–anchovy population dynamics model assessing nonlinear controls of anchovy and gelatinous biomass in the Black Sea. Mar Ecol Prog Ser 369:229–256. https://doi.org/10.3354/meps07540
48. Gucu AC, Inanmaz ÖE, Ok M, Sakinan S (2016) Recent changes in the spawning grounds of Black Sea anchovy, *Engraulis encrasicolus*. Fish Oceanogr 25(1):67–84. https://doi.org/10.1111/fog.12135
49. Gucu AC, Genc Y, Dagtekin M, Sakinan S, Ak O, Ok M et al (2017) On Black Sea anchovy and its fishery. Rev Fish Sci Aquac 25(3):230–244. https://doi.org/10.1080/23308249.2016.1276152
50. Chashchin A, Shlyakhov VA, Dubovik VE, Negoda S (2015) Stock assessment of anchovy (*Engraulis encrasicolus* L.) in Northern Black Sea and Sea of Azov. In: Zlateva I, Raykov V, Nikolov N (eds) progressive engineering practices in marine resource management. IGI Global, Hershey, pp 209–243
51. Güraslan C, Fach BA, Oguz T (2017) Understanding the impact of environmental variability on anchovy overwintering migration in the Black Sea and its implications for the fishing industry. Front Mar Sci 4:275. https://doi.org/10.3389/fmars.2017.00275
52. Akkuş G, Gucu AC (2023) First maturity size of the Black Sea anchovy and its implications on the age-based stock assessment models. Acta Biol Turc 36(3):1–10
53. Ulman A, Zengin M, Demirel N, Pauly D (2020) Corrigendum: the lost fish of Turkey: a recent history of disappeared species and commercial fishery extinctions for the Turkish Marmara and Black Seas. Front Mar Sci 7:600242. https://doi.org/10.3389/fmars.2020.600242
54. Daskalov GM, Demirel N, Ulman A, Georgieva Y, Zengin M (2020) Stock dynamics and predator–prey effects of Atlantic bonito and bluefish as top predators in the Black Sea. ICES J Mar Sci 77(7–8):2995–3005. https://doi.org/10.1093/icesjms/fsaa152
55. Oguz T (2007) Nonlinear response of Black Sea pelagic fish stocks to overexploitation. Mar Ecol Prog Ser 345:211–228
56. Oguz T (2017) Controls of multiple stressors on the Black Sea fishery. Front Mar Sci 4:110. https://doi.org/10.3389/fmars.2017.00110
57. Şahin C, Ceylan Y (2023) Determination of age, growth parameters and first sexual maturity length of horse mackerel (*Trachurus mediterraneus* Steindachner, 1868) in the eastern Black Sea Region. J Anatol Environ Anim Sci 8(1):69–79. https://doi.org/10.5229/jaes.1218067
58. Cheung W, Sarmiento J, Dunne J et al (2013) Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nat Clim Change 3:254–258. https://doi.org/10.1038/nclimate1691
59. Bektas Y, Belduz AO (2008) Molecular phylogeny of Turkish trachurus species (Perciformes: Carangidae) inferred from mitochondrial DNA analyses. J Fish Biol 73:1228–1248. https://doi.org/10.1111/j.1095-8649.2008.01996.x
60. Dürrani Ö, Seyhan K (2024) Stock identification of the Mediterranean horse mackerel (Carangidae: *Trachurus trachurus*) in the Marmara and Black Seas using body and otolith shape analyses. Estuar Coast Shelf Sci 299:108687. https://doi.org/10.1016/j.ecss.2024.108687
61. URL-3. FishBase. *Scophthalmus maximus* summary page. https://fishbase.mnhn.fr/summary/Scophthalmus-maximus.html. Accessed 29 Nov 2024
62. Giragosov V, Khanaychenko A (2012) The state-of-art of the Black Sea turbot spawning population off Crimea (1998–2010). Turk J Fish Aquat Sci 12:377–383
63. Hulak B, Leonchyk Y, Maximov V, Tiganov G, Shlyakhov V, Pyatnitsky M (2021) The current state of the turbot, *Scophthalmus maximus* (Linnaeus, 1758), population in the northwestern part of the Black Sea. Fish Aquat Life 29:164–175. https://doi.org/10.2478/aopf-2021-0018
64. Acara, A. (1985). The Black Sea Turbot. State Planning Orga-nization, Ankara, Turkey (in Turkish).
65. Zlateva I, Ivanova P, Dzhembekova N, Doncheva V, Popov I, Slabakova V, Raev Y, Raykov V, Dimitrov D (2023) Spatial distribution and genetic diversity of turbot (*Scophthalmus maximus*, Linnaeus, 1758) in Bulgarian Black Sea waters relative to fishing pressure and their abiotic environment. J Mar Sci Eng 11(10):1982. https://doi.org/10.3390/jmse11101982
66. Yıldız T, Uzer U, Yemişken E, Karakulak FS, Kahraman AE, Çanak Ö (2021) Conserve immatures and rebound the potential: stock status and reproduction of whiting (*Merlangius merlangus* [Linnaeus, 1758]) in the Western Black Sea. Mar Biol Res 17(9–10):815–827. https://doi.org/10.1080/17451000.2021.2019787
67. Karadurmuş U (2022) Current status, management, and future prospects of whiting (*Merlangius merlangus*) in the Sea of Marmara. Acta Aquat Turc 18(3):314–331
68. Garcia AM, Vieira JP, Winemiller KO, Raseira MB (2004) Reproductive cycle and spatiotemporal variation in abundance of the one-sided livebearer *Jenynsia multidentada* in Patos Lagoon, Brazil. Hydrobiologia 515(1–3):39–48
69. Şahin C, Öztürk E, Emanet M, Ceylan Y (2021) Determination of age, growth, and first maturity length of whiting (*Merlangius merlangus*, Nordmann, 1840) in the Eastern Black Sea. Acta Aquat Turc 17(4):450–462
70. Gür Ü, Gürkanlı CT, Çiftci Y (2023) Genetic structure and demographic history of whiting *Merlangius merlangus* (Linnaeus, 1758) populations distributed in Turkey inferred from variation in mitochondrial DNA sequences. Acta Adriat 64(2):157–168. https://doi.org/10.32582/aa.64.2.9
71. Grant WS, Bowen BW (1998) Shallow population histories in deep evolutionary lineages of marine fishes: insights for sardines and anchovies and lessons for conservation. J Hered 89(5):415–426. https://doi.org/10.1093/jhered/89.5.415
72. Sağlam NE, Sağlam C (2012) Population parameters of whiting (*Merlangius merlangus* euxinus L., 1758) in the southeastern Black Sea. Turk J Fish Aquat Sci 12:831–839. https://doi.org/10.4194/1303-2712-v12_4_11
73. Alexandrov BG, Zaitsev YP (1998) Black Sea biodiversity in eutrophication conditions. In: Kotlyakov V, Uppenbrink M, Metreveli V (eds) Conservation of the biological diversity as a prerequisite for sustainable development in the black sea region. NATO ASI Ser, vol 46. Springer, Dordrecht, pp 221–240
74. Tokarev Y, Shulman G (2007) Biodiversity in the Black Sea: effects of climate and anthropogenic factors. Hydrobiologia 580:23–33. https://doi.org/10.1007/s10750-006-0468-6
75. Byrne M, Gall M, Wolfe K, Agüera A (2016) From pole to pole: the potential for the Arctic seastar *Asterias amurensis* to invade a warming Southern Ocean. Glob Change Biol 22:3874–3887. https://doi.org/10.1111/gcb.13309
76. Carlos LA, Barbosa NPU, Moulton TP, Creed JC (2015) Ecological niche model used to examine the distribution of an invasive, nonindigenous coral. Mar Environ Res 103:115–124. https://doi.org/10.1016/j.marenvres.2014.12.007
77. Bianchi CN (2007) Biodiversity issues for the forthcoming tropical Mediterranean Sea. Hydrobiologia 580(1):7–21. https://doi.org/10.1007/s10750-006-0456-4
78. Lejeusne C, Chevaldonné P, Pergent-Martini C, Boudouresque CF, Pérez T (2010) Climate change effects on a miniature ocean: the highly diverse, highly impacted Mediterranean Sea. Trend Ecol Evol 25(4):250–260
79. Mallett MC, Thiem JD, Butler GL, Kennard MJ (2024) A systematic review of approaches to assess fish health responses to anthropogenic threats in freshwater ecosystems. Conserv Physiol 12(1):coae022. https://doi.org/10.1093/conphys/coae022
80. Free CM, Mangin T, Molinos JG, Ojea E, Burden M, Costello C et al (2020) Realistic fisheries management reforms could mitigate the impacts of climate change in most countries. PLoS ONE 15(3):e0224347. https://doi.org/10.1371/journal.pone.0224347

Publisher's Note