Possible Changes of *Pinus nigra* Distribution Regions in Türkiye with the Impacts of Global Climate Change

Uğur Cantürk,[a,]* İsmail Koç,[b] Halil Barış Özel,[c] and Hakan Şevik [d]

Global climate change poses significant threats to ecosystems worldwide, particularly impacting long-lived forest tree species such as *Pinus nigra*. This study assessed the potential shifts in distribution areas for *Pinus nigra*, an important tree species, one highly vulnerable to global climate change, given its prevalence in continental climates, in Türkiye under different climate scenarios (SSPs 585 and 245). In this study, suitable distribution regions of *Pinus nigra* were evaluated based on SSPs 585 and SSPs 245 using nine different models. Results indicated potential losses in *Pinus nigra* distribution areas ranging from 15.0% to 43.5% (SSPs 245) and 19.7% to 48.9% (SSPs 585) by 2100. However, in 2100, new suitable distribution areas are expected to be formed at rates ranging from 13.8% to 32.1% and 15.1% to 34.4% according to the above scenarios. Because most of the newly formed suitable distribution regions are quite far from the areas where the species currently spreads, it seems necessary to provide the migration mechanism needed by the species by humans to prevent population losses in this process.

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*Contact information: a: Department of Forest Engineering, Düzce University, Düzce, 81620 Türkiye; b: Department of Forest Engineering, Düzce University, Düzce, 81620 Türkiye; c: Department of Forest Engineering, Bartın University, Bartın, 74100 Türkiye; d: Department of Environmental Engineering, Kastamonu University, Kastamonu,37150 Türkiye; * Corresponding author: ugurcanturk55@gmail.com*

INTRODUCTION

The impact of the industrial revolution has led to the world's population density in urban areas in the last century (Dogan *et al*. 2022) and, therefore, to an increase in fossil fuel consumption to meet energy demands (Yayla *et al*. 2022; Koc *et al*. 2023). Environmental pollution and global climate change occur in conjunction with each other as a result of pollution caused by industrial activities, vehicles, and other anthropogenic factors (Ghoma *et al*. 2023; Isinkaralar *et al*. 2023), and especially atmospheric pollution (Cobanoglu *et al*. 2023a; Key *et al*. 2023; Sulhan *et al*. 2023), urbanization (Kilicoglu *et al*. 2021; Istanbullu *et al*. 2023). Global climate change (Varol *et al*. 2021) has emerged as the most critical worldwide issue. These problems, especially urbanization and global climate change, are irreversible challenges that the world must confront globally (Tekin *et al*. 2022).

Among these problems, it is emphasized that global climate change, which is stated to affect all ecosystems, is now irreversible, and that changes related to the process should be predicted and precautions should be taken on a sectoral basis to mitigate its destructive consequences (Tekin *et al*. 2022; Cobanoglu *et al*. 2023b). Studies show that the environmental community most affected by this process is plants. Studies have also revealed that the most prominent outcomes of global climate change will manifest themselves in the form of temperature increase and drought (Koç 2022; Koç and Nzokou 2023). Because the changes will occur in a much shorter period than plants can adapt, plants that do not have adequate mobility will have difficulty adapting to the process, and individual, population, and even species losses will be inevitable (Varol *et al*. 2021).

Forest ecosystems are among the ecosystems that will feel the effects of the process the most because their main elements are trees with long life cycles. Therefore, for forests to survive the global climate change process with the least damage and to minimize population and species losses, it is crucial to predict possible alterations in the suitable distribution regions of trees, which are the main elements of forest areas, and take the necessary precautions. Different climate models and scenarios have been used in studies on this topic (Ardestani and Ghahfarrokhi 2021; Adhikari *et al*. 2022; Zhang and Wang 2023). However, to make the most accurate predictions, it is crucial to evaluate the possible results using different models and verify which models and scenarios are realized by monitoring the process and take the required protections.

Black pine (*Pinus nigra* Arnold.), which is one of the most common pine species, especially in the Mediterranean basin (semi-arid and arid region) in the south of Türkiye, is one of the most widespread and economically significant native conifers in Türkiye (Atalay and Efe 2010, 2012). Black pine is a drought-sensitive species that has been the subject of many scientific studies in Türkiye (Martín-Benito *et al*. 2008; Köse *et al*. 2012). It also will be affected by climate change and future projections, whose effects have been increasing over the last half-century (Andreu *et al*. 2007; Martin-Benito *et al*. 2011; Sánchez-Salguero *et al*. 2012). Many studies have reported that forests in the Mediterranean basin are affected by elevated temperatures and drought (Piovesan *et al*. 2008; Charru *et al*. 2017; Cetin *et al*. 2023). Meteorological data have revealed that the temperature in Türkiye has been on an increasing trend in the last 30 years and that the rainfall in the southern and western parts of the country has decreased in the last 70 years (Köse *et al*. 2017).

The current study aimed to determine the suitable distribution regions of black pine (*P. nigra*) in Türkiye and is of particular significance because this tree species is most frequently introduced into dryland regions, depending on different models and scenarios. The study aims are as follows:

1. To reveal the differences between these climate models using different climate models to determine the prediction accuracy of these models,
2. To compare the results of these scenarios using two different scenarios,
3. To determine the shift of suitable distribution areas in the same area in Türkiye according to different scenarios and climate models rather than the total suitable distribution area (suitable areas today *versus* 2060 and 2100; unsuitable areas today *versus* 2060 and 2100).
4. To determine the models that give the most accurate results by comparing the results of the used models with the actual distribution areas today.

Many studies have tried to determine how the suitable distribution areas of different plant species will change due to global climate change with the help of various models. Within the scope of this study, the changes in the suitable distribution areas of black pine were determined using nine different models. Thus, the aim was to determine the models with the most reliable and usable results among the models used for this purpose. The species in which the study was conducted is one of the most drought-resistant species (Topacoglu *et al.* 2016; Yigit *et al.* 2023). For this reason, the study is also crucial in determining the shift in suitable distribution areas of one of the most drought-resistant species due to the effects of global climate change.

EXPERIMENTAL

Türkiye has approximately 21 million hectares of forest areas. Within that area, 19.8% of Türkiye’s forest is covered with black pine (*P. nigra* Arnold.) forests (approx. 4.2 million hectares) (OGM 2015). In this study, the database of black pine was used, which has a wide distribution area within the borders in Türkiye and is of particular importance as it is used for plantation, forestation, afforestation, and recreational purposes, and is one of the species most introduced into the continental climate.

In the current research, distribution data with precisely geo-referenced coordinates were collected from publicized literature, herbarium archives, field surveys, and online sources of ‘Euforgen’ (https://www.euforgen.org/species/pinus-nigra/) and ‘Global Biodiversity Information Facility’ (https://www.gbif.org, GBIF 2023). The sampling prejudice correlated to occurrence reports (Aiello-Lammens *et al*. 2015) was cleared by the spatial thinning method, wherein a single existence spot was maintained in 1 × 1 km^2 grid cell dimensions. For carrying out community distribution modeling of *P. nigra*, a total of 120 geo-referenced presence reports eventually employed spatial thinning. The distribution areas of black pine in Türkiye are presented in Fig. 1.

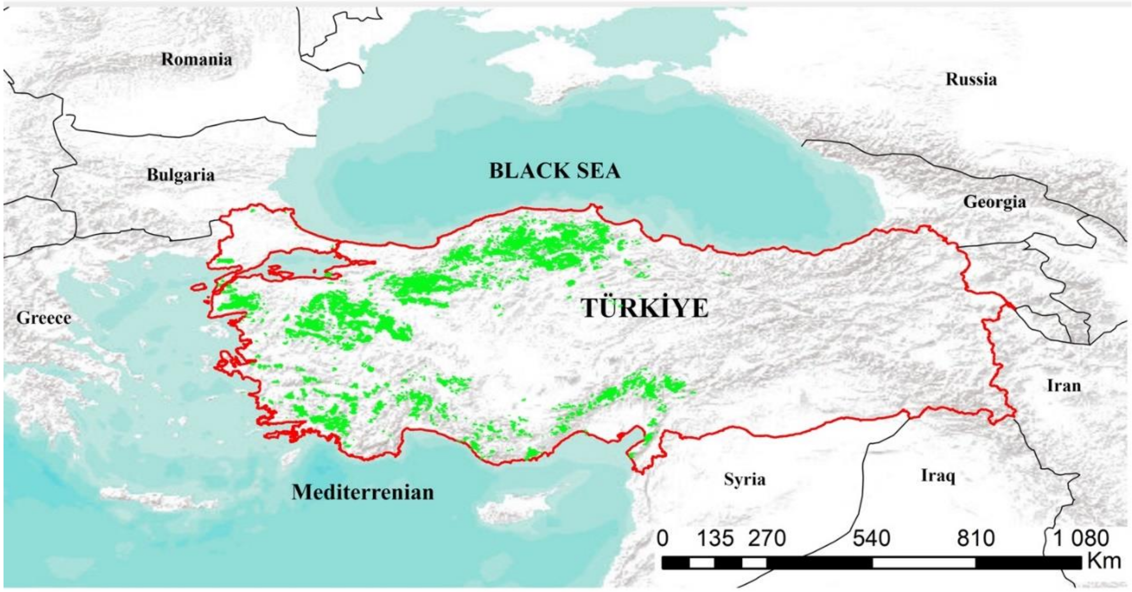

Fig. 1. Distribution regions of black pine in Türkiye

The authors obtained bioclimatic information from the WorldClim database version v2.1 (Fick and Hijmans 2017) (http://www.worldclim.org) at a spatial resolution of 30 arcseconds (~ 1 km). For this goal, 19 distinct bioclimatic parameters were used based on Shared Socio-economic Pathways (SSPs) 585 and 245 global climate change scenarios explained in the 2021 Intergovernmental Panel on Climate Change (IPCC) 6th Assessment

Report (AR6) for the years 2060 and 2100 in the WorldClim database (Table 1). The AR6 featuring Center National de Recherches Météorologiques model version 6 [CNRM-CM6-1-HR (France)] of the IPCC with two scenarios of representative concentration pathways (SSPS 585 and SSPS 245) for two time periods (2060 and 2100) (Hamid *et al*. 2019) were utilized to estimate the coming possible *P. nigra* distribution. The current approach is among the most robust and reliable climate models used in numerous scientific research and fully mimics various climatic phenomena (Mushtaq *et al*. 2021; Bhat *et al*. 2023; Sofi *et al*. 2023). The authors assessed multicollinearity in bioclimatic parameters using Pearson's correlation test to enhance model reliability and minimize inaccurate outcomes (Hamid *et al*. 2019; Sofi *et al*. 2023). A single bioclimatic parameter was chosen from a pair of associated variables with '$r > 0.75$ or < -0.75' correlation coefficient (Hamid *et al*. 2019; Rather *et al*. 2022; Bhat *et al*. 2023). The selected variables are marked with asterisks in Table 1.

Table 1. Bioclimatic Parameters Used in this Research

BIO1*	Annual Mean Temperature
BIO2*	Mean Diurnal Range [Mean of monthly (max temp - min temp)]
BIO3*	Isothermality (BIO2/BIO7) (×100)
BIO4*	Temperature Seasonality (standard deviation ×100)
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5-BIO6)
BIO8*	Mean Temperature of Wettest Quarter
BIO9	Mean Temperature of Driest Quarter
BIO10	Mean Temperature of Warmest Quarter
BIO11	Mean Temperature of Coldest Quarter
BIO12*	Annual Precipitation
BIO13	Precipitation of Wettest Month
BIO14*	Precipitation of Driest Month
BIO15*	Precipitation Seasonality (Coefficient of Variation)
BIO16	Precipitation of Wettest Quarter
BIO17	Precipitation of Driest Quarter
BIO18	Precipitation of Warmest Quarter
BIO19*	Precipitation of Coldest Quarter

* = Selected variables

The niche species distribution technique is the most preferred procedure in examining the geographical distribution of plant species under climate change (Varol *et al*. 2021, 2022a; Zhao *et al*. 2021; Varol *et al*. 2022a; Bhat *et al*. 2023). Niche modeling techniques were created based on Niche theory, which is based on ecological principles and some specific algorithms related to these principles. The features of plant niches are determined by examining the existing geographical distribution of plants and various relevant environmental variable factors to predict optimum growing environments for plant species (Zhang *et al*. 2019; Zhao *et al*. 2021).

Each species distribution approach has pros and cons due to dissimilar algorithms and principles. Biomod, a modeling platform based on R software to improve the precision of predictions, was designed in 2003 and has been widely chosen in numerous studies since then (Bi *et al*. 2013; Zhao *et al*. 2021). This software package can be accessed *via* the CRAN web page (cran.r-project.org). It contains the subsequent species distribution modeling algorithms: surface range envelope (SRE) modeling (Busby 1991), generalized additive models (GAMs) (Guisan *et al*. 2002), generalized linear models (GLMs) (Guisan *et al*. 2002), classification tree analysis (CTA) (Vayssi'eres *et al*. 2000), generalized boosted models (GBMs) (Elith *et al*. 2008), artificial neural networks (ANNs) (Lek and Gu'egan 1999), random forest (RF) (Breiman 2001), flexible discriminant analysis (FDA) (Hastie *et al*. 1994), maximum entropy (MAXENT) (Phillips *et al*. 2006), and multivariate adaptive regression splines (MARS) (Friedman 1991).

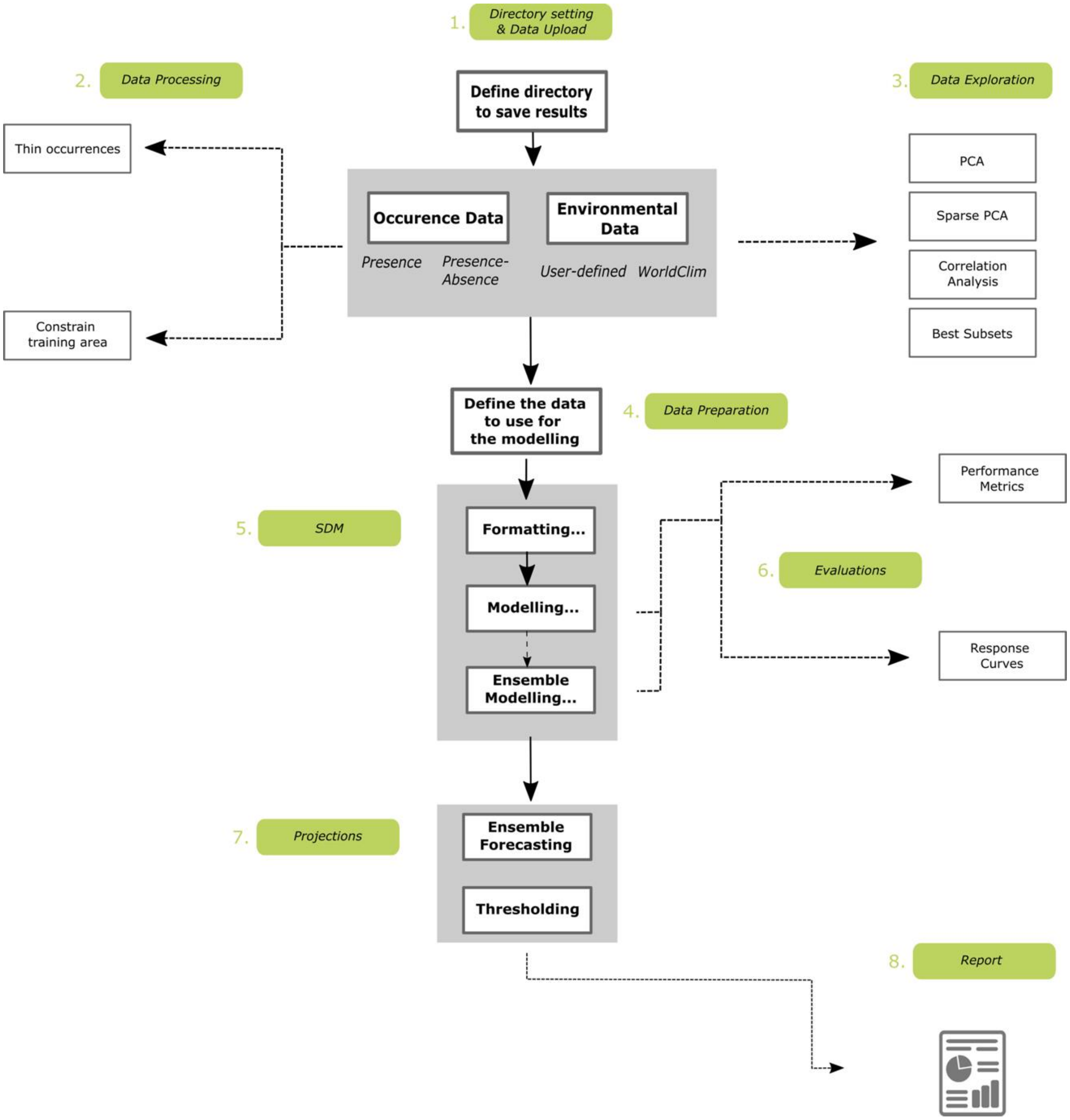

Fig. 2. The ShinyBIOMOD workflow diagram (Obtained from https://gitlab.com/IanOndo/shinybiomod/-/blob/master/README.md)

The ShinyBIOMOD, a graphical interface for the R package “biomod2,” was operated in the present research to facilitate the SDMs (Species Distribution Models) approach (Thuiller *et al*. 2009, 2016). To train and apply the models, a geographical region was defined in the *P. nigra* distribution maps in the stand maps created by the Republic of Türkiye, General Directorate of Forestry. Afterward, the occurrence data was uploaded of *P. nigra* previously created and 19 bioclimatic variables. Because the dataset solely included existence reports, three pseudo-absence datasets of 120 randomly created pseudo-absence spots were created to operate the SDMs. Nine distinct SDMs (explained by Franklin 2010) were run to model *P. nigra* distribution. The used models were CTA, GBM, ANN, GAM, FDA, GLM, RF, MAXENT, and MARS. This modeling approach was made using the instructions defined at 'https://gitlab.com/IanOndo/shinybiomod/-/blob/master/README.md', and the workflow chart is exhibited in Fig. 2. Some studies have recently given a detailed explanation of this model (Henderson *et al*. 2022; Kass *et al*. 2023; Sillero *et al*. 2023).

Pseudo-absence and occurrence spots were randomly split into verification (20%) and training data (80%). To specify model statistics and *P. nigra* species distribution, three replicates were run for all models on each of three pseudo-absence datasets (9 total replicates for each model). Area Under the Curve (AUC) error evaluation data, Receiver Operating Characteristics (ROC), and True Skill Statistic (TSS) were used to evaluate the performances of each model recurrence (Allouche *et al*. 2006; Fawcett 2006; Canturk and Kulaç 2021; Varol *et al*. 2021). Lastly, ensemble models were built to estimate *P. nigra* distribution across all nine modeling approaches. The authors designed three distinctive projections of *P. nigra* distribution operating ensemble modeling outputs. These outcomes were estimated binary predictions of absence/presence, likelihood of occurrence, and forecasted probability of presence by committee agreement of binary separated model outcomes. Binary projections were built by generating a threshold of calculated possibility to maximize the perceptiveness and accuracy of the model. This situation indicates that a threshold (TSS and ROC ≥ 0.8) was used for probability estimations to the accurate negative ratio (specificity) and maximize the accurate positive ratio (sensitivity) through the whole range. Pixels with probability weights above the threshold were classed as presences, and pixels below the threshold were classified as absences. The current modeling method was employed and described in detail in a paper on American chestnuts by Henderson *et al*. (2022). The current procedure lets the client specify and modify a model by changing the initial situations, classifications, model parameters, and boundary circumstances to acquire the most reasonable prediction outcomes (Luo *et al*. 2017).

In the current study, the existing suitable distribution territories of the species were first distinguished according to the models used. In the next stage, the suitable distribution regions of the species in 2060 and 2100 were modeled according to SSPs 245 and SSPs 585 scenarios. Then, the proportional changes in 2060 and 2100 according to the suitable distribution areas today were calculated and evaluated according to different models.

RESULTS

Accuracy statistics for each distribution approach are shown in Table 2. These illustrate the average values for ROC and TSS across all model repetitions. The ROC values expand from 0 to 1 and represent the likelihood that assigning a forecasted fitness weight at a random spot of presence is higher than setting a predicted fitness weight at a random dot of absence (Fawcett 2006). The TSS expands from −1 to 1, with 0 denoting an approach that acts no better than random guesses (Fawcett 2006; Henderson *et al*. 2022). The AUC values of 0.6 and 0.7 are commonly decoded as "fair" models, and ROC weights between 0.7 and 0.8 are meant as "good" models.

Table 2. Comparison of *Pinus nigra* Distribution Models' Performance Based on Each Model's Validation Data against the Test Data

Technique	ROC	TSS
ANN	0.876	0.654
CTA	0.941	0.814
FDA	0.807	0.441
GAM	0.813	0.518
GBM	0.957	0.817
GLM	0.757	0.394
MARS	0.862	0.545
MAXENT	0.866	0.556
RF	0.999	0.986

Suitable distribution areas of *P. nigra* throughout Türkiye were determined according to different models, and suitable distribution area maps are given in Fig. 3, and numerical values of distribution areas are given in Table 3.

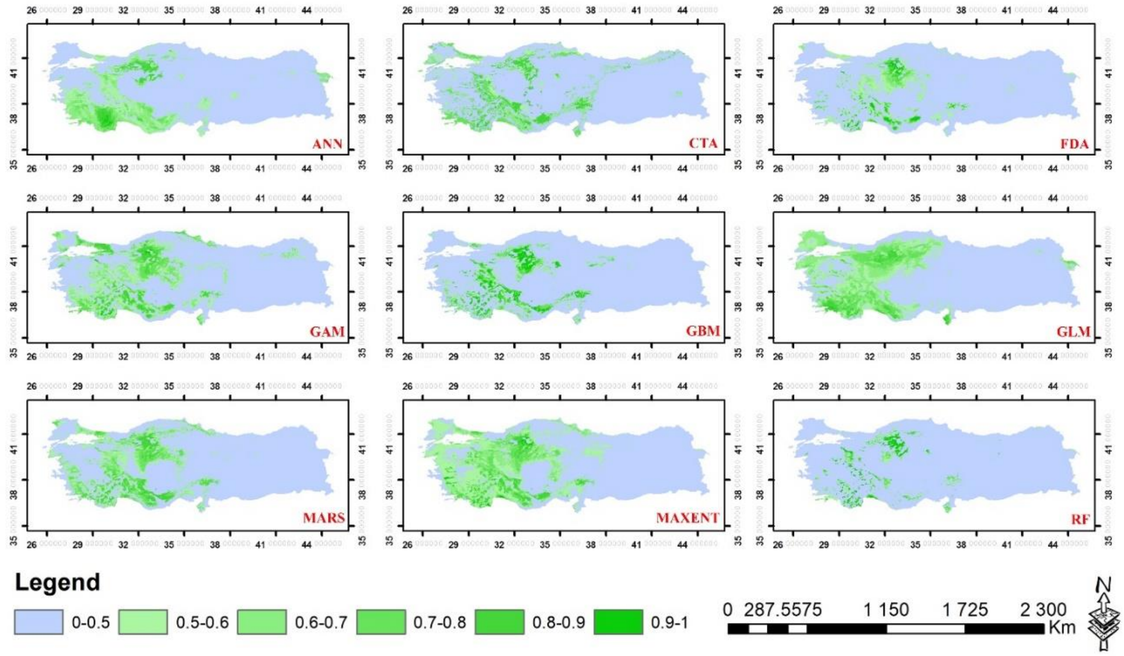

Fig. 3. Current suitable distribution areas of *Pinus nigra*

It can be seen that the suitable distribution regions for *P. nigra* vary considerably according to different models, and, generally, the northern and southwestern parts of the central part of Türkiye are suitable regions for the distribution of the species in all models (Fig. 3). The models that offer the broadest suitable distribution area for the species are

MAXENT (37.58%), GLM (34.27%), and GAM (29.33%), while the models that offer the narrowest distribution area are RF (7.71%), FDA (14.79%), and GBM (15.47%) (Fig. 3 and Table 3). Regarding the SSPs 245 scenario, the suitable distribution regions of the *P. nigra* in 2060 are given in Fig. 4, and the numerical data are shown in Table 4.

Table 3. Current Areal Distribution of Suitable Distribution Areas of *Pinus nigra*

Suitability	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
0.0 to 0.5	76.57	79.7	85.21	70.67	84.53	65.73	74.81	62.42	92.29
0.5 to 0.6	10.22	5.27	7.70	11.42	3.83	12.97	8.55	18.82	2.32
0.6 to 0.7	7.79	5.13	3.10	8.35	3.49	12.27	7.01	9.48	1.66
0.7 to 0.8	2.97	5.57	1.88	5.79	3.16	6.82	6.56	5.85	1.25
0.8 to 0.9	2.24	4.33	1.20	3.56	2.48	2.15	3.07	3.06	0.97
0.9 to 1.0	0.21	0	0.91	0.21	2.51	0.06	0	0.37	1.51

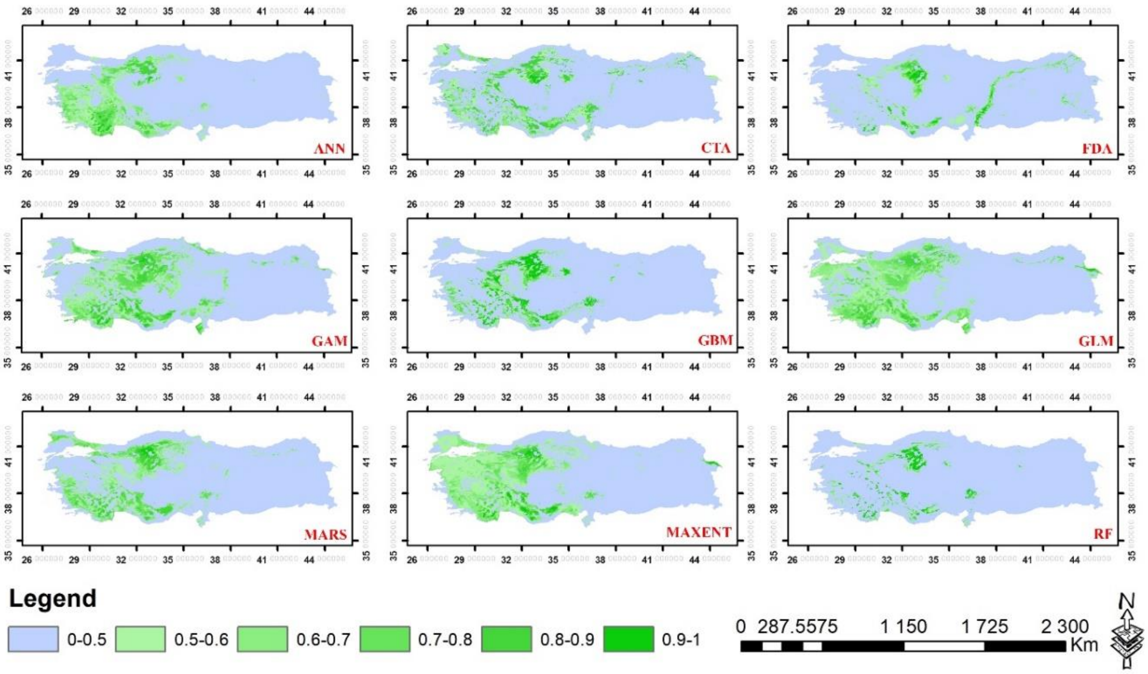

Fig. 4. Suitable distribution areas of *Pinus nigra* in 2060 based on the SSPs 245 scenario

Table 4. Suitable Distribution Areas of *Pinus nigra* in 2060 Based on the SSPs 245

	SSPs 245_2060								
Suitability	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
0.0 to 0.5	78.50	79.19	87.72	69.51	84.32	66.90	76.81	65.81	92.71
0.5 to 0.6	8.62	8.68	5.31	10.26	4.03	12.47	7.86	16.97	2.12
0.6 to 0.7	6.86	5.15	2.81	8.87	3.27	10.95	6.81	9.45	1.42
0.7 to 0.8	3.67	0.21	2.07	6.79	2.95	6.72	5.33	4.31	1.06
0.8 to 0.9	2.08	6.35	1.25	4.22	2.56	2.87	2.87	2.58	0.82
0.9 to 1	0.27	0.42	0.84	0.35	2.87	0.09	0.32	0.88	1.87

When Fig. 4 and Table 4 are examined, it is predicted that there will be a slight increase in the suitable distribution regions of *P. nigra* until 2060, only according to the GAM (1.16%), CTA (0.51%), and GBM (0.21%) models. According to all other models, the suitable distribution regions of *P. nigra* will decrease compared to today, and this decrease may reach 3.39%, 2.51%, and 2% in the total area according to MAXENT, FDA, and MARS, respectively. Considering the suitable distribution area, it is predicted that the suitable distribution regions of *P. nigra* may decrease nearly 17% (according to FDA) in 2060, according to the SSPs 245 scenario. Regarding the SSPs 245, the suitable distribution regions of the *P. nigra* in 2100 are given in Fig. 5, and its numerical data are given in Table 5.

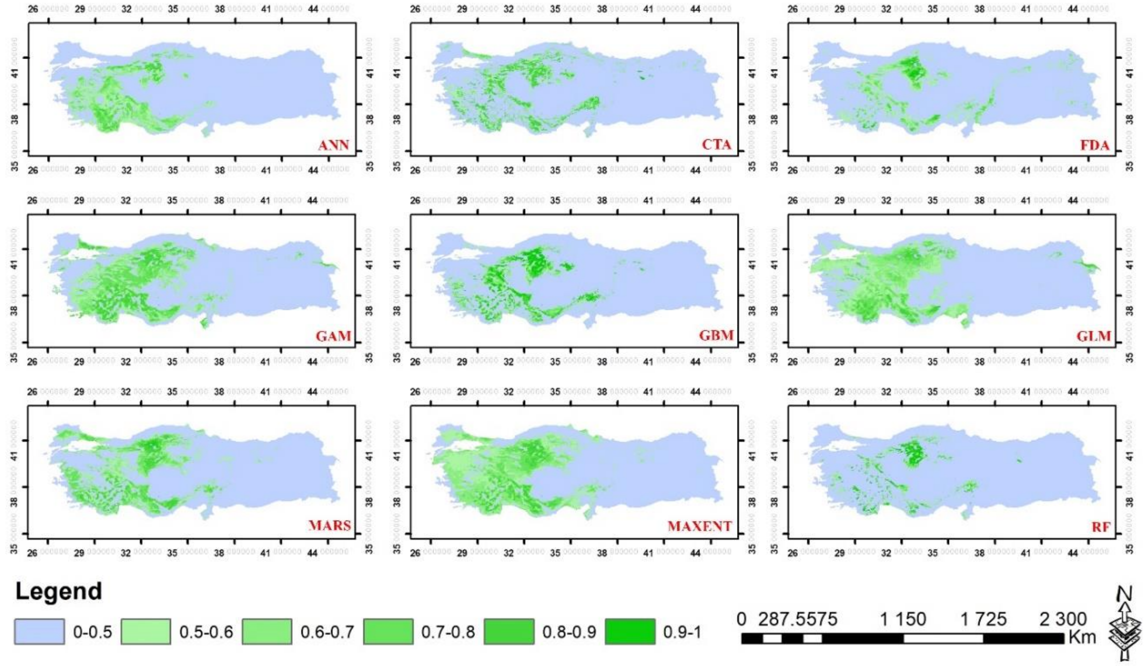

Fig. 5. Suitable distribution areas of *Pinus nigra* in 2100 based on the SSPs 245 scenario

Table 5. Suitable Distribution Areas of *Pinus nigra* in 2100 Based on the SSPs 245 Scenario

	SSPs 245_2100								
Suitability	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
0.0 to 0.5	79.47	84.18	84.92	68.78	83.44	67.09	74.10	63.32	91.73
0.5 to 0.6	8.32	3.31	7.22	8.98	3.79	13.67	7.59	13.85	2.28
0.6 to 0.7	6.91	6.13	3.83	9.17	3.44	11.42	7.64	13.14	1.74
0.7 to 0.8	4.05	0.96	2.34	8.81	3.03	5.86	7.36	6.35	1.40
0.8 to 0.9	1.25	5.00	1.22	4.24	3.20	1.94	3.16	3.31	1.33
0.9 to 1.0	0	0.42	0.47	0.02	3.10	0.02	0.15	0.03	1.52

Regarding the SSPs 245 scenario, the suitable distribution regions of *P. nigra* will increase in 2100, unlike 2060, according to most of the models subject to the study (Fig. 5 and Table 5). This increase will be seen primarily in the FDA, MARS, and MAXENT models regarding total area. According to the CTA model, the suitable distribution regions of the *P. nigra* will decrease significantly compared to 2060, and there will be a slight decrease according to the ANN and GLM models. It was defined how the appropriate distribution regions of the species will change between now and 2100. This change is shown on the map in Fig. 6, and its numerical data is given in Table 6.

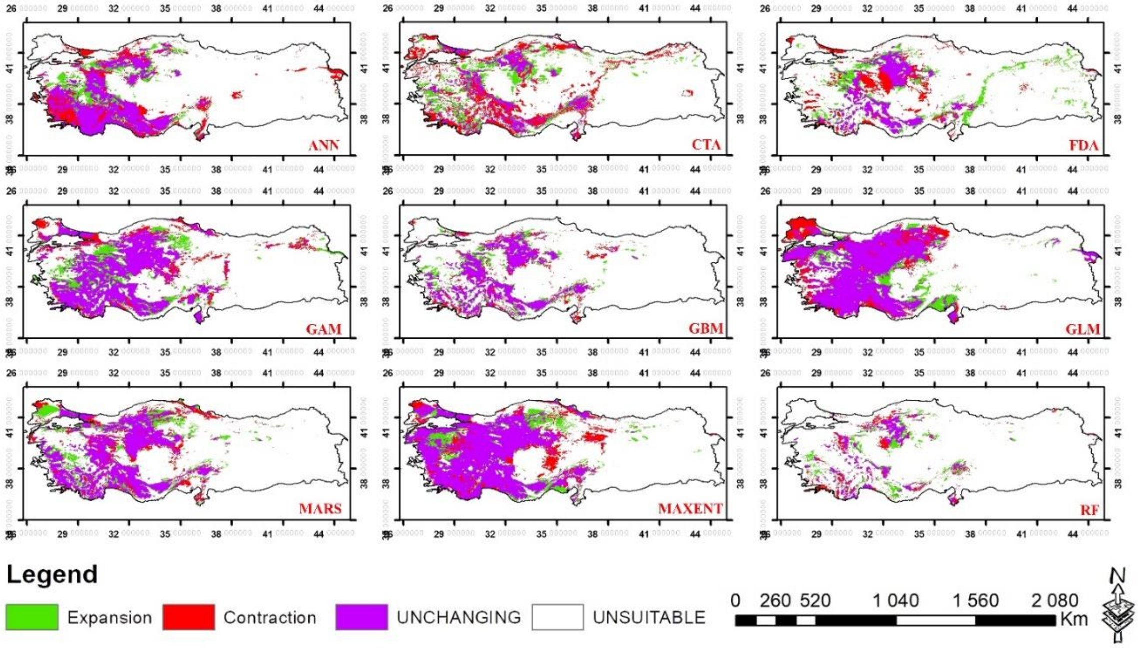

Fig. 6. Changes in suitable distribution areas of *Pinus nigra* in 2100 compared to today, based on the SSPs 245 scenario

Table 6. Changes in Suitable Distribution Areas of *Pinus nigra* in 2100 Compared to Today, Based on the SSPs 245 Scenario

	Total Area (%)								
	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
Unsuitable	71.58	72.01	78.52	63.27	80.11	60.26	68.56	56.38	88.61
Unchanging	15.54	8.12	8.38	23.82	12.13	27.4	19.62	30.63	4.61
Contraction	7.89	12.18	6.41	5.52	3.35	6.86	5.56	6.94	3.12
Expansion	4.99	7.69	6.69	7.39	4.41	5.48	6.26	6.05	3.66
	Suitable Area Changing (%)								
	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
Unchanging	54.68	29.01	39.01	64.85	60.99	68.95	62.41	70.22	40.48
Contraction	27.76	43.52	29.84	15.03	16.84	17.26	17.68	15.91	27.39
Expansion	17.56	27.47	31.15	20.12	22.17	13.79	19.91	13.87	32.13

It is apparent that the suitable distribution regions of *P. nigra* vary according to different models (Table 6). In 2100, the same areas as today will remain suitable distribution areas for *P. nigra*, with rates varying between 29.01% (CTA) and 70.22% (MAXENT). However, suitable distribution areas will decrease 43.52% and 15.03%, according to the CTA and GAM models, respectively, until 2100 compared to today. However, some regions that are not proper for *P. nigra* today will be suitable for the species in 2100. The expansion ratio of these areas varies between 13.79% (GLM) and 32.13% (RF) (Table 6).

It is predicted that population losses will be mainly seen in the central parts and the northwestern and southwestern ends, but according to most of the models, suitable distribution areas will occur in the north of the central parts and the north of the southern parts, that is, in the northern Anatolian Mountains range and the parts behind the Taurus Mountains range (Fig. 6). According to the FDA model, it is projected that proper distribution regions will occur in the inner parts of the eastern parts of Türkiye (Fig. 6). Regarding the SSPs 585 scenario, the suitable distribution regions of the *P. nigra* in 2060 are given in Fig. 7, and the numerical data are given in Table 7.

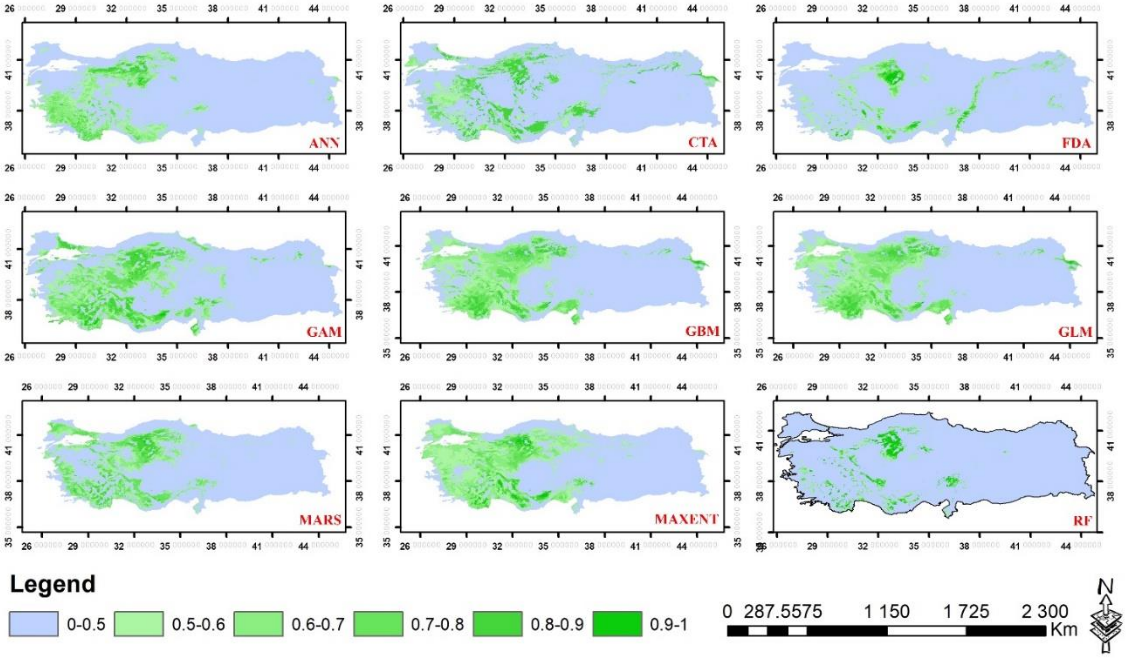

Fig. 7. Suitable distribution areas of *Pinus nigra* in 2060 based on the SSPs 585 scenario

Table 7. Suitable Distribution Regions of *Pinus nigra* in 2060 Based on the SSPs 585 Scenario

	SSPs 585_2060								
Suitability	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
0.0 to 0.5	79.47	79.45	87.2	67.14	84.2	65.51	73.98	61.62	92.14
0.5 to 0.6	8.66	6.19	6.39	10.07	4.41	12.78	7.93	17.48	2.05
0.6 to 0.7	7.25	5.87	2.94	10.17	3.34	11.66	8.52	12.77	1.38
0.7 to 0.8	3.20	2.09	1.76	7.76	2.65	6.99	6.92	4.95	1.32
0.8 to 0.9	1.38	6.32	1.05	4.61	2.42	2.98	2.60	2.41	1.19
0.9 to 1.0	0.04	0.08	0.66	0.25	2.98	0.08	0.05	0.77	1.92

When Fig. 7 and Table 7 are examined, the suitable distribution areas of *P. nigra* will decrease until 2060 only according to the ANN (2.90%) and FDA (1.99%) models, while there will be a slight increase in the suitable distribution regions of the species according to other models. While this increase will generally be at most 0.8%, according to the GAM model, it will be 3.53%. Regarding the SSPs 585, the suitable distribution regions of the *P. nigra* in 2100 are given in Fig. 8, and the numerical data are given in Table 8.

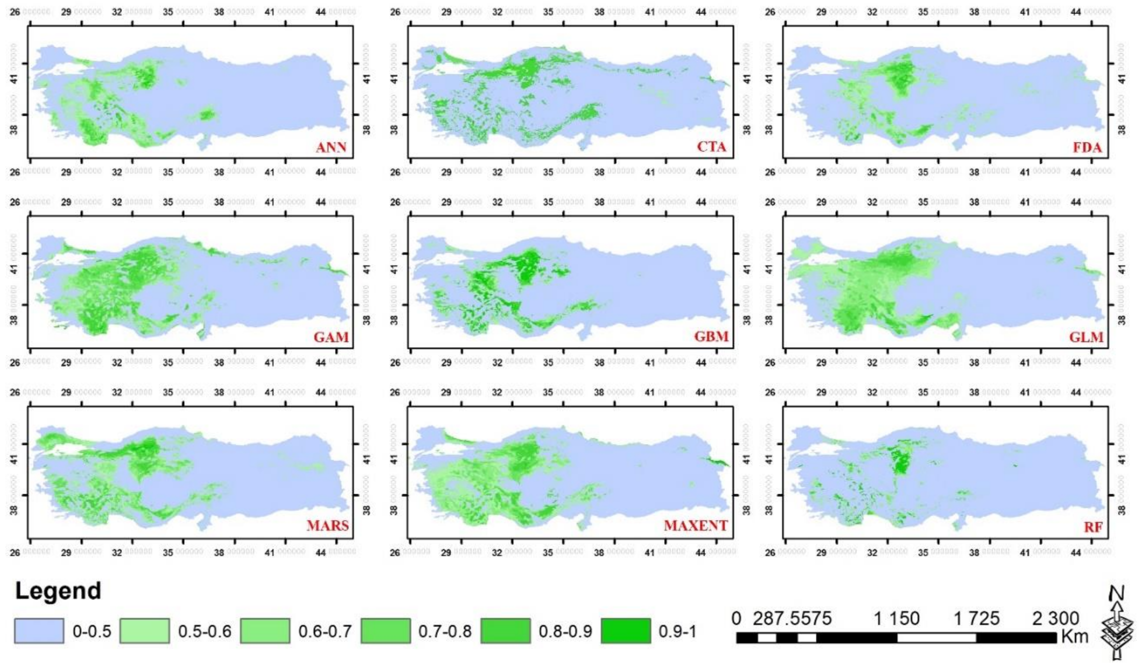

Fig. 8. Suitable distribution areas of *Pinus nigra* in 2100 based on the SSPs 585 scenario

Table 8. Suitable Distribution Regions of *Pinus nigra* in 2100 Based on the SSPs 585 Scenario

	SSPs 585_2100								
Suitability	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
0.0 to 0.5	80.73	85.99	83.11	68.25	83.26	67.78	73.34	69.66	91.43
0.5 to 0.6	8.81	1.73	8.13	8.18	3.81	12.29	8.76	11.62	2.64
0.6 to 0.7	5.69	0	4.56	8.77	3.03	11.05	7.86	9.56	2.08
0.7 to 0.8	2.98	1.59	2.47	9.56	2.97	6.32	6.29	5.55	1.32
0.8 to 0.9	1.60	10.59	1.55	5.15	3.64	2.50	3.49	3.40	1.13
0.9 to 1.0	0.19	0.10	0.18	0.09	3.29	0.06	0.26	0.21	1.40

According to the SSPs 585 scenario, unlike 2060, there will be a decrease in the suitable distribution regions of *P. nigra* in 2100, according to most of the models subject to the study. An increase of 4.09% is predicted only according to the FDA model, and some increases are predicted to be less than 1% according to the GBM, MARS, and RF models. According to other models, it is predicted that there will be a momentous decrease in the distribution regions of the species, and this decrease may be 6.54% (CTA model) or even 8.04% (MAXENT model) of the country's surface area. It was defined how the proper distribution regions of the species will change according to the SSPs 585 scenario from now until 2100. This change is shown on the map in Fig. 9, and its numerical data is given in Table 9.

It is shown that the changes in suitable distribution regions for *P. nigra* vary according to different models (Table 9). In 2100, the same areas as today will remain suitable distribution areas for *P. nigra*, with rates varying between 25.09% (CTA) and 59.76% (MAXENT). However, today's suitable distribution areas will decrease 48.92% and 19.73% until 2100, according to the CTA and GAM models, respectively. However, some areas that are not suitable for *P. nigra* today will be suitable distribution regions for the species in 2100. The expansion ratio of these areas varies between 15.11% (GLM) and 34.44% (RF).

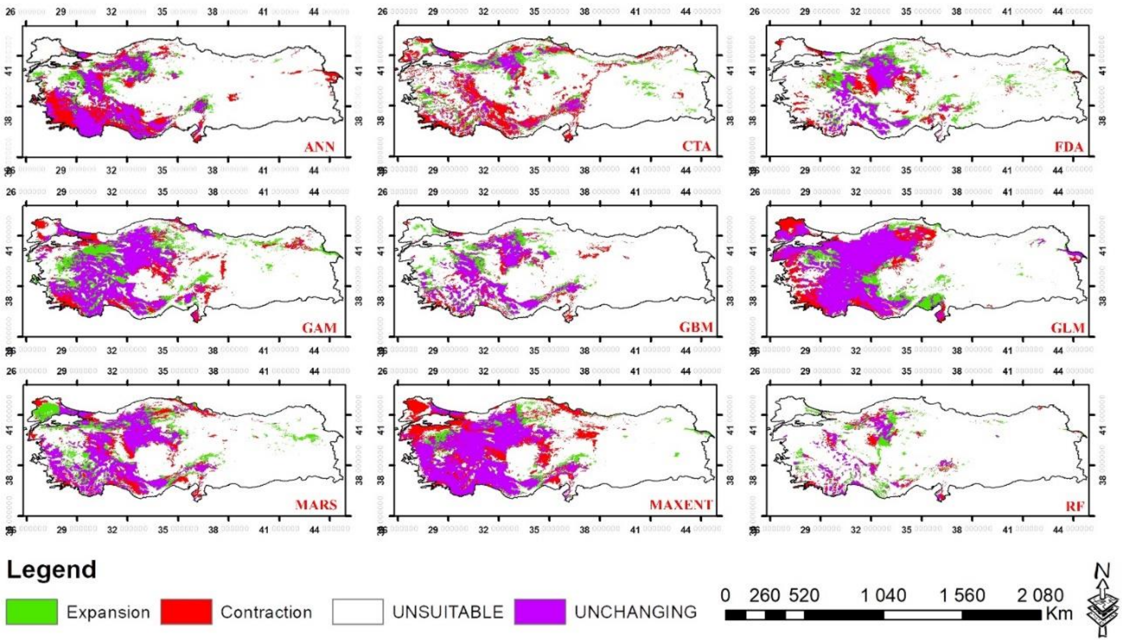

Fig. 9. Changes in suitable distribution areas of *Pinus nigra* in 2100 compared to today, based on the SSPs 585 scenario

Table 9. Change in Suitable Distribution Areas of *Pinus nigra* in 2100 Compared to Today, Based on the SSPs 585 Scenario

	Total Area (%)								
	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
Unsuitable	71.68	72.57	77.45	60.46	78.83	59.64	66.32	57.49	88.22
Unchanging	14.38	6.88	9.12	21.54	11.04	26.12	18.15	25.40	4.51
Contraction	9.05	13.42	5.67	7.80	4.44	8.15	7.03	12.17	3.22
Expansion	4.88	7.13	7.76	10.20	5.69	6.10	8.50	4.93	4.06
	Suitable Area Changing (%)								
	ANN	CTA	FDA	GAM	GBM	GLM	MARS	MAXENT	RF
Unchanging	50.79	25.09	40.45	54.47	52.15	64.70	53.89	59.76	38.25
Contraction	31.97	48.92	25.14	19.73	20.97	20.19	20.87	28.64	27.31
Expansion	17.24	25.99	34.41	25.80	26.88	15.11	25.24	11.60	34.44

According to Fig. 9, it is predicted that population losses will be mainly seen in the central parts and southwestern edges. In contrast, according to most models, suitable distribution areas will occur east of the central parts of Türkiye. According to the FDA, CTA, GAM, and MARS models, appropriate distribution regions are projected to occur in the inner parts of the eastern parts of Türkiye.

DISCUSSION

In this study, using a total of 9 models, changes in the suitable distribution areas for *P. nigra* today and in the future were determined according to SSPs 245 and SSPs 585 scenarios. The models used in the study have been the subject of different studies for similar purposes, as seen in Table 10, and the appropriate distribution areas of those species have been determined with the models used.

Table 10. Models Used Suitable Distribution Areas of Some Different Species for Similar Purposes

Author(s)	Used Models	Species
Dutra Silva *et al*. (2019)	GLM, GAM, ANN	*Pittosporum undulatum, Acacia melanoxylon, Acacia faya*
Zhang *et al*. (2020)	RF	*Anredera cordifolia*
Williams *et al*. (2009)	GLM, ANN, RF	*Harmonia stebbinsii, Riogonum libertini, Leptosiphon nuttallii*
Taleshi *et al*. (2019)	GLM, CTA, ANN, GBM	*Quercus brantii*
Ardestani and Ghahfarrokhi (2021)	GLM, GBM, CTA, ANN, FDA, RF	*Salvia hydrangea*
Alavi *et al*. (2019)	GAM, CTA, RF	*Taxus baccata*
Zhang and Wang (2023)	GLM, FDA, RF, GBM	*Meconopsis punicea*
Safaei *et al*. (2021)	MAXENT, MARS	*Quercus brantii*
Sung *et al*. (2018)	MARS, GLM, GAM	*Solenopsis invicta*
Adhikari *et al*. (2022)	ANN, GLM, MARS, MAXENT, RF	*Ambrosia artemisiifolia, Solanum carolinense, Ageratina altissima, Sicyos angulatus, Symphyotrichum pilosum, Ambrosia trifida, Lactuca serriola, Rumex acetosella, Paspalum distichum, Hypochaeris radicata, Solidago altissima, and Paspalum dilatatum*

The results of the study show that there will be substantial alterations in the possible distribution regions of *P. nigra* because of climate change, based on all models. However, the outputs of each model vary greatly. Undoubtedly, it is challenging to determine which of these models gives the most reliable results. However, when the current distribution area of the species in Türkiye is compared with the appropriate distribution areas according to different models, it is seen that the closest results are obtained in the MAXENT and GAM models. This result leads to the conclusion that these models' future distribution area predictions are likely to be more accurate. These models were used in many studies conducted in Türkiye (Varol *et al*. 2021; Tekin *et al*. 2022), and appropriate distribution area change predictions were made for different tree species. Among these models, the AUC and TSS values of the MAXENT model were 0.866 and 0.556, while the AUC and TSS values of the GAM model were calculated as 0.813 and 0.518, respectively. The higher AUC and TSS values of these model predictions mean that they are more consistent than other models, and similar explanations are also expressed in other studies. Generalized linear models and artificial neural networks had the lowest AUC and TSS values (Henderson *et al*. 2022). In many studies, the AUC value is close to the weights achieved (approved good models) in this study. In a study where seven different models were compared, it was stated that the TSS and AUC values of the models varied between 0.315 and 0.698 and 0.715 and 0.915, respectively (Dutra Silva *et al*., 2019), while in another study, the TSS and AUC values varied between 0.21 and 0.69 and 0.65 and 0.90 (Taccoen *et al*. 2019). In another study where five different models were evaluated, TSS and AUC values were calculated to vary between 0.71 and 0.9 and 0.93 and 0.98 based on models (Wouyou *et al*. 2022).

The study results show that today's suitable distribution areas will decrease 15.0% to 43.5% and 19.7% to 48.9% according to the SSPs 245 and SSPs 585 scenario by 2100, respectively. This result is generally consistent with the literature that studies generally conclude that the outcomes of global climate change will induce a significant decrease in the suitable distribution regions of tree species (Cantürk and Kulaç 2021; Varol *et al*. 2021; Varol *et al*. 2022a,b). Some studies conducted in Türkiye have determined that there will be a notable decrease in the suitable distribution regions of *Tilia cordata*, *Tilia tomentosa*, and *Tilia platypyllos*, and that this decrease may result in a 15% loss in *Tilia platypyllos* (Cantürk and Kulaç 2021). In a study conducted on *Fraxinus excelsior*, while the current potential distribution region of the species is 165,900 ha, it was calculated that this area will be 153,300 ha and 155,800 ha according to the SSPs 245 and SSPs 585 scenario in 2100, respectively (Varol *et al*. 2021). As a result of another study, it was concluded that *Carpinus betulus* may experience population losses exceeding 25% at altitudes below 1600 m, and *Carpinus orientalis* may experience population losses exceeding 30% at altitudes below 1000 m (Varol *et al*. 2022a). It is also estimated that *Buxus sempervirens* may experience losses not exceeding 6% in the years 2040 to 2060 (Varol *et al*. 2022b), and *Abies bornmuelleriana*'s suitable distribution regions at elevations of 1800 to 2000 m may decrease to 38.5% of today's level in 2100 (Tekin *et al*. 2022).

In studies conducted on pine species, it is generally predicted that there will be population losses. For instance, in a study conducted in Greece, they determined that losses of suitable distribution area could be up to 45% for *Pinus halepensis*, 54% for *Pinus brutia*, and 77% for *P. nigra*, depending on different scenarios (Fyllas *et al*. 2022). In a study conducted in Türkiye, it is stated that the suitable distribution region for *P. nigra*, which is 25650 km^2 today, will decrease to 6060 km^2 and 3070 km^2 in 2070, respectively, regarding RCP 4.5 and RCP 8.5 scenarios, meaning a loss of approximately 88% may occur (Arslan and Örücü 2019).

As a result of this study, it is projected that new distribution regions will emerge in 2100, according to some scenarios. The expansion ratio of suitable areas ranges between 13.79% to 32.13% and 15.11% to 34.44% according to the SSPs 245 and SSPs 585 scenario, respectively. Many studies predict that suitable distribution regions for different species will be created due to the global climate change effect (Yu *et al*. 2006; Varol *et al*. 2021, 2022b). This change actually means that the distribution regions suitable for some tree species will turn into suitable distribution regions for other plant species (Dyderski *et al*. 2018; Cantürk and Kulaç 2021; Fyllas *et al*. 2022). For example, broad-leaved deciduous and mixed forests are predicted to expand towards the north of China (Yu *et al*. 2006). Dyderski *et al*. (2018) state that while the distribution ranges of *Fraxinus excelsior*, *Fagus sylvatica*, *Quercus petraea, Abies alba,* and *Quercus robur* are expanding, there will be a narrowing in the distribution regions of *Pinus sylvestris*, *Larix decidua*, *Betula* *pendula*, and *Picea abies*. Similarly, it is generally stated that the suitable distribution regions of the species will shift upwards in altitude, and this shift will be at different levels on a species basis; for example, it will range between 233 m to 650 m for *Quercus frainetto* (Fyllas *et al*. 2022).

However, creating suitable distribution areas will not prevent population losses. It is emphasized that since trees do not have effective mobility, they will be incapable of migrating to newly formed suitable distribution areas, and this will cause large population and even species losses. In this case, it is stated that to minimize the effects of the process, it is necessary to provide the migration mechanism needed by the trees by people (Tekin *et al*. 2022). For example, as the study results show, suitable distribution regions are expected to occur in the inner parts of the eastern parts of Türkiye. However, *P. nigra* does not have distribution areas in these regions, and it is not possible to transport the seeds to these regions naturally.

The effects of global climate change are estimated to emerge in multiple ways. Plant development is shaped by the interaction of genetic structure (Kurz *et al*. 2023) and environmental factors (Kuzmina *et al*. 2023; Tandogan *et al*. 2023). Among the environmental factors, climate is one of the most critical environmental factors affecting all plant phenotypic characters (Cesur *et al*. 2022; Özel *et al*. 2022; Erdem *et al*. 2023). It is estimated that global climate change will significantly affect climate parameters, especially precipitation and temperature (Koç and Nzokou 2022; Cetin *et al*. 2023). It is also stated that the most apparent effects of global climate change will be temperature increase and drought, and possible effects will include changing rainfall regimes, longer growing seasons, and increased summer drought (Huang *et al*. 2020). Although the effects of these changes are uncertain, increasing temperatures will certainly increase insect damage and the number of forest fires (Ertugrul *et al*. 2021).

Changing climate conditions will cause responses in plant species, such as acclimatization, adaptation locally, migration, and loss of vitality (Benito Garzon *et al*. 2019; Gárate-Escamilla *et al*. 2019). At the same time, climate change may have adverse effects, such as the invasion of exotic species into the area, and positive outcomes, such as increased wood production due to elevated CO_2 levels (Brundu and Richardson 2016; Walker *et al*. 2019). In addition, the process and severity of plant species being affected by climate change will vary significantly, and changes in climatic parameters will cause stress factors to emerge. Stress factors also negatively affect plant development (Ozel *et al*. 2021; Koç and Nzokou 2023). Therefore, it is stated that the impact of global climate change on species will impact species in the area and in terms of development, quality, and health (Daniel *et al*. 2017). For example, it has been stated that radial tree growth may decrease 20% in *Toona ciliate*, *Lagerstroemia speciosa*, and *Chukrasia tabularis* species, and it has been emphasized that this situation may have serious consequences, especially on tropical forest carbon balance (Rahman *et al*. 2018).

Another critical factor that will affect the possible responses of species to global climate change will be microclimatic and micro-edaphic conditions. Studies reveal that microenvironmental conditions can be more effective than main climate types (Sevik *et al*. 2021; Yigit *et al*. 2021). According to these results, the consequences of global climate change will differ at the regional and even local levels (Taylor *et al*. 2017). As can be seen, the consequences of global climate change create results that affect species and individuals through the interaction of many factors. However, as the study results show, the most appropriate models that can be used to determine these effects have yet to be determined, and there is a big difference between the model outputs used.

Future research should focus on more sensitive and detailed local studies to improve understanding and accuracy of prediction. This includes producing new models tailored to changing climate and environmental conditions for various species. Additionally, artificial migration of species to regions with projected suitable growing environments should be considered to promote ecosystem resilience in the face of climate change.

CONCLUSION

1. The study utilized nine different models and two scenarios to assess potential changes in suitable distribution areas for *P. nigra* until 2100. Notably, there were significant disparities between model outputs and scenario results, suggesting the importance of ongoing monitoring and consideration of both model and scenario outcomes to improve predictive accuracy.
2. The MAXENT and GAM models demonstrated the closest alignment with observed distribution areas compared to other models. Consequently, it is recommended that these models be prioritized in future studies to enhance the reliability of predictions regarding *P. nigra* distribution.
3. The study projects a significant reduction in *P. nigra* suitable distribution areas, with potential losses exceeding 40% by 2100. While new suitable areas may emerge, natural colonization is unlikely. Therefore, foresters must facilitate migration mechanisms to prevent higher-than-anticipated population losses. Adjustments to forest management plans based on study results are advised to address this issue effectively.
4. The study found that the MAXENT and GAM models produced more accurate results than the other models. However, it is essential to validate these findings through more comprehensive studies. Moreover, it is recommended to conduct field studies to assess the practicality and reliability of each model, which will be instrumental in guiding future research in this field.
5. Modeling studies carried out to date have mainly used the models that have been considered in the present work. However, new models need to be developed, and existing models need to be improved in light of new findings and reports regarding the process and developing technologies.

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