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The Extinction Trajectory of the Crimean Juniper (*Juniperus excelsa*) Species in Central Anatolia Under Global Climate Change

İç Anadolu'daki Boylu Ardıç (*Juniperus excelsa*) Türünün Küresel İklim Değişikliği Altında Yok Oluşa Sürüklenişi

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Abstract

The Crimean juniper (*Juniperus excelsa*) species belonging to the Juniperus genus, which is a species native to various harsh environments, exhibits remarkable resilience, especially in droughts. However, due to changing climate conditions on a global scale, Crimean juniper distribution is at a critical junction. This study aims to delineate both the current and potential distribution models of Crimean juniper in the Central Anatolian region. To achieve this, the Maximum Entropy (MaxEnt) modelling approach was employed, incorporating environmental and climatic variables from the Chelsa dataset. The model results identified mean annual air temperature, elevation, precipitation of the driest month, and roughness index as key contributors to the species current distribution. The model demonstrated strong performance, with an AUC of 0.888 for the training dataset and 0.792 for the test dataset, classifying it as a "good model". In this context, simulations were conducted for the years 2070 and 2100 under three different scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5), based on the current distribution map of Crimean juniper. The simulation outcomes indicated that by 2070, the species' distribution will experience significant decrease and fragmentation, with the potential for near complete disappearance by 2100. In conclusion, this study underscores the detrimental impacts of global climate change on the distribution of Crimean juniper in the Central Anatolian region.

Keywords: Crimean juniper, Climate change, Geographical distribution, Maximum entropy, Modelling and mapping

Özet

Juniperus cinsine ait olan ve çeşitli zorlu ortamlara özgü bir tür olan Boylu ardıç (*Juniperus excelsa*) türü, özellikle kuraklıklarda dikkate değer bir dayanıklılık sergilemektedir. Ancak, küresel ölçekte değişen iklim koşulları nedeniyle, Boylu ardıç dağılımı kritik bir durumdadır. Bu çalışma, Orta Anadolu bölgesinde Boylu ardıçın hem mevcut hem de potansiyel dağılım modeli ve haritalanması ortaya koyulması amaçlamaktadır. Bunu başarmak için, Chelsa veri setindeki iklim ve çevresel değişkenlerin modellenmesini sağlayan Maksimum Entropi (*MaxEnt*) modelleme yaklaşımı kullanılmıştır. Boylu ardıç model sonuçları, ortalama yıllık hava sıcaklığını, yüksekliği, en kurak ayın yağışını ve pürüzlülük indeksini türün mevcut dağılımına önemli katkıda bulunanlar olarak belirlemiştir. Model, eğitim veri seti için 0,888 ve test veri seti için 0,792'lik bir AUC ile güçlü bir performans göstererek onu "iyi bir model" olarak sınıflandırmıştır. Bu bağlamda, Boylu ardıçın güncel dağılım haritasına dayanarak, üç farklı senaryo (SSP1-2.6, SSP3-7.0 ve SSP5-8.5) altında 2070 ve 2100 yılları için simülasyonlar yürütülmüştür. Simülasyon sonuçları, türün dağılımının 2070 yılına kadar önemli ölçüde azalacağını ve parçalanacağını, 2100 yılına kadar ise neredeyse tamamen yok olma potansiyeline sahip olduğunu göstermiştir. Sonuç olarak, bu çalışma küresel iklim değişikliğinin Orta Anadolu bölgesinde Kırım ardıcının dağılımı üzerindeki olumsuz etkilerini vurgulamaktadır.

Anahtar Kelimeler: Boylu ardıç, İklim değişikliği, Coğrafi dağılım, Maksimum entropi, Modelleme ve haritalama

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1. Introduction

Climate change has irreversible effects on natural resources such as forest ecosystems (Millar et al., 2007; Shakir Hanna, 2025). Therefore, important problems have been raised by researchers recently regarding global climate change (Akbaş et al., 2023; Gül and Esen, 2024; Gül, 2025; Moe, 2025). Despite the inherently natural dynamics of global climate change, its progression has been significantly altered by ongoing anthropogenic factors, diverging from its expected natural course (Jump and Peñuelas, 2005). Therefore, to predict the possible consequences of climate change, it has generally focused on the ecological characteristics of plant and wild animal species distributed in forest ecosystems (Dormann, 2007; Acarer and Mert, 2024; Tekeş and Özkan, 2024).

Forest ecosystems have many positive effects on issues such as protecting biodiversity and wildlife, as well as regulating the climate, increasing soil fertility, and preventing erosion (Brockerhoff et al., 2017; Mori et al., 2017). Therefore, humans have benefited from forest ecosystems both directly and indirectly to meet their nutritional, shelter and protection needs (Imbert et al., 2021). One of these benefits is the issue of non-wood forest products, the use and importance of which is increasing. Non-wood forest products, which are traded worldwide and have very high material value, contribute greatly to the economic situation of humans. Medicinal and aromatic plants, which have product potential especially for areas such as the food industry, cosmetics, medicine and pharmacy, are the most significant non-wood forest products that make significant contributions to the economies of countries (Özkan et al., 2015; Gülsoy and Çıvğa, 2016; Özdemir et al., 2020)

Juniper (*Juniperus* sp.,) genus, distributed in wide geographical areas, contain the tree species with the most important medicinal and aromatic plant potential (Gülsoy, 2015; Özkan et al., 2015). There are approximately more than 70 species of the Juniper genus in the world and are generally distributed in the northern hemisphere (Adams and Hagerman, 1977; Adams, 2014). In Turkey, the Juniper genus is represented by seven species (*Juniperus sabina, Juniperus phoenicia, Juniperus oxycedrus, Juniperus foetidissima, Juniperus excelsa, Juniperus drupacea, Juniperus communis*), the most common of which are Crimean juniper (*Juniperus excelsa*), Foetid juniper (*Juniperus foetidissima*) and Prickly juniper (*Juniperus oxycedrus*) species (Eliçin, 1977; Özdemir et al., 2020a; Tekeş, 2024). All these taxa are generally defined as “juniper” among the public and the Crimean juniper has the widest distribution area (Özkan et al., 2010a; Özdemir et al., 2020a). In Turkey, the boiled fruit extract of the Crimean juniper is widely used for colds, for the treatment of gastrointestinal disorders, as an expectorant, as a diuretic to treat kidney stones, to treat calcification, and against urinary tract infections (Gulsoy et al., 2019).

Crimean juniper can be found in shrub form as well as in trees that can grow up to a height of approximately 8-30 m (Hall, 1984). It is distributed in different elevation, slope and aspect classes in Turkey. Crimean juniper, which cannot form pure stands, can be found in the lower layer of primary forest tree stands due to its shade tolerance. In general, Crimean juniper is one of the important plants of the Mediterranean and Central Anatolian hard-leaved forest and shrub vegetation. This species occupies rocky and stony slopes of mountains, that is, areas with low physiological depth and mostly sunny areas (Eliçin, 1977; Anşin and Özkan, 1993).

There are some studies on the composition of essential oils of Crimean juniper, which is distributed in wide geographical areas in Turkey, estimation of its potential distribution, antimicrobial activity of aqueous and methanol extracts, biogeography and genetic relationships of taxa, leaf anatomy of species, composition of essential oils, actual and potential distribution mapping (Doğan et al., 2011; Özdemir et al., 2020; Özcan et al., 2023).

Although Central Anatolia, one of Turkey's seven regions, is believed to host a significant distribution of Crimean juniper, there is currently a lack of research examining the effects of global climate change on the species in this region. Accordingly, the aim of this study was to assess the distribution of Crimean juniper under various temporal and climate change scenarios. For this purpose, the study employed environmental factors alongside climatic variables derived from the Chelsa dataset. Potential distribution maps of Crimean juniper under various current and future scenarios and time periods were created using the MaxEnt (Maximum Entropy) modelling approach.

2. Material and Method

2.1. Study area

Junipers, one of the primary forest trees in Turkey, have a wide distribution area. In terms of area covered, it ranks third in Turkey after the red pine and the black pine. Therefore, juniper species have an important place in forest ecosystems in terms of both area and wealth (Eliçin, 1997; Gulcu et al., 2005; Çıvğa, 2015). Based on this, Özcan et al. (2023) found that the current distribution of the Crimean juniper (*Juniperus excelsa*) species in the Central Anatolian region of Turkey is higher than in other regions. However, in this study only a large-scale (worldwide) study area was selected for species distribution and environmental variables were not considered. Based on this, the Central Anatolia region, where Crimean juniper distribution is predicted to be high, constitutes the area of the study (Fig 1).

2.2. Crimean juniper (*Juniperus excelsa*) presence data

The presence data of Crimean juniper, which is estimated to be distributed in the Central Anatolia Region, were obtained from the GBIF (Global Biodiversity Information Facility) internet address (GBIF, 2025). The presence data downloaded on a world scale were resized to the Turkish scale. The coordinate system suitable for the recorded presence data was defined, and a total of 198 occurrence points for the target species (Crimean juniper) were visualized on the map using green markers. (Fig 1).

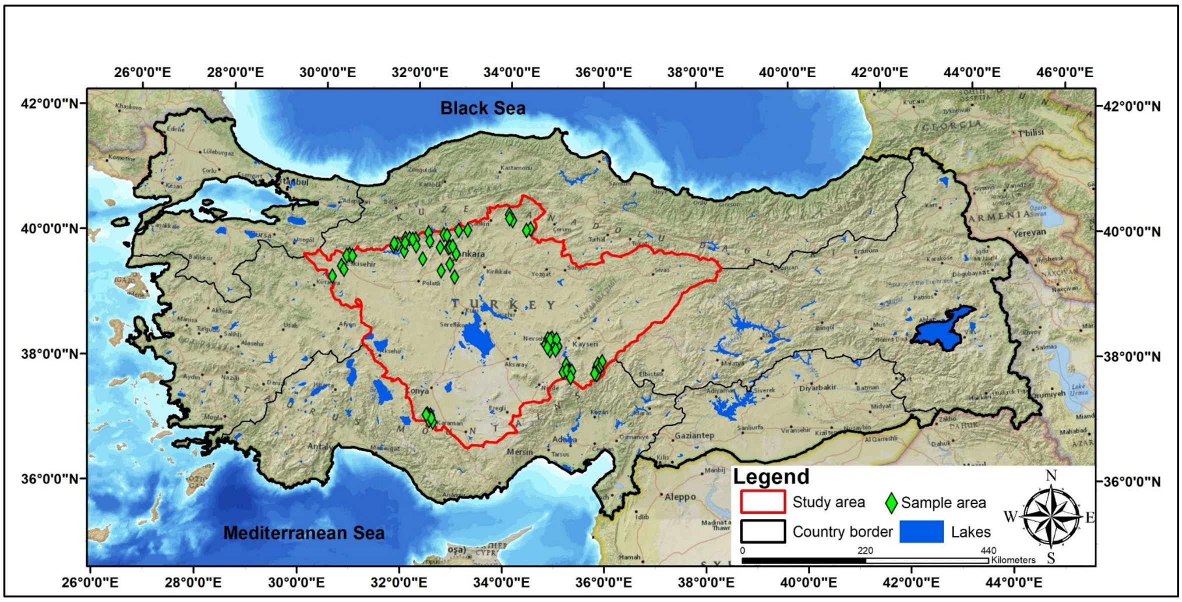


Figure 1. Location map of the study area and Crimean juniper (*Juniperus excelsa*) presence data.

2.3. Production of environmental and climatic variables

Model-based studies come to the forefront to determine the numerical actual and potential distribution areas of plant species distributed in forest ecosystems (Elith and Leathwick, 2009). Digital base maps need to be produced for model-based species distributions (Beery et al., 2021). The digital base maps to be generated should be aligned with the boundaries of the study area and standardized to the same spatial resolution and coordinate reference system. For this reason, a world-scale high-resolution digital elevation model was obtained from the https://www.usgs.gov/ internet address. Based on the digital elevation model of the study area, environmental variables of the study area were created using the ArcGIS Pro software. Some of the environmental variables frequently preferred in plant species distribution modelling are as follows, and these variables were used in the modelling study: slope classes, landuse classification, topographic position, elevation (Tekeş et al., 2024a; Tekeş et al., 2024b), slope length and steepness factor, aspect, heat load, compound topographic, elevation classes, aspect classes, slope, ruggedness, roughness index, hill shade index, solar illumination and area solar radiation (Corsi et al., 2000; Saffariha et al., 2023).

Following the generation of environmental variables specific to the study area, the development of global climate variables was initiated. To project future changes in climate conditions at a global scale, a variety of climate models and scenarios have been proposed. Global Climate Models (*GCMs*) and Shared Socioeconomic Pathways (*SSPs*) serve as essential tools for forecasting potential shifts in the distribution of main species, such as Crimean juniper, under future climate conditions. GCMs simulate climate dynamics and provide projections of critical variables, including temperature and precipitation. Among the widely used sources of climate data, WorldClim and Chelsa are frequently utilized for current and future climate modelling. Chelsa offers high-resolution climate data for terrestrial regions, with temperature estimates derived through a statistical downscaling approach applied to atmospheric temperature profiles. The current CHELSA bioclimatic dataset, derived from High Resolution Climate Surfaces (version 2.1) available at https://chelsa-climate.org/, includes 19 bioclimatic variables generated through spatial interpolation of gridded historical climate data. The bioclimatic variables are as follows: Bio1 represents the mean annual air temperature, bio2 refers to the mean diurnal temperature range, and bio3 captures isothermality. Bio4 corresponds to temperature seasonality, while bio5 and bio6 are the mean daily maximum air temperature of the warmest month and the mean daily minimum air temperature of the coldest month, respectively. bio7 indicates the annual range of air temperature, and bio8, bio9, bio10, and bio11 represent the mean daily mean air temperatures for the wettest, driest, warmest, and coldest quarters, respectively. Regarding precipitation, bio12 denotes the total annual precipitation, while bio13 and bio14 represent the precipitation amount for the wettest and driest months, respectively. bio15 addresses precipitation seasonality, and bio16, bio17, bio18, and bio19 refer to the mean monthly precipitation amounts for the wettest, driest, warmest, and coldest quarters, respectively. (Brun et al., 2022; Karger et al., 2023). In addition, future climate (2070 and 2100) change projections from the CMIP6-based Geophysical Fluid Dynamics Laboratory Earth System Model within the Chelsa climate model were used in the study. This projection models biogeochemical cycles in conjunction with climate systems by incorporating advanced representations of land surfaces, atmosphere, seas, and oceanic ice. These high-resolution models are progressively refined in response to ongoing climate change within the Earth's system. Therefore, to assess both the current and potential distribution of Crimean juniper, three Shared Socioeconomic Pathways (*SSPs*) -specifically SSP1-2.6, SSP3-7.0 and SSP5-8.5- were integrated, each representing different future scenarios in two separate time periods: 2070 and 2100.

2.4. Modelling & Simulation process

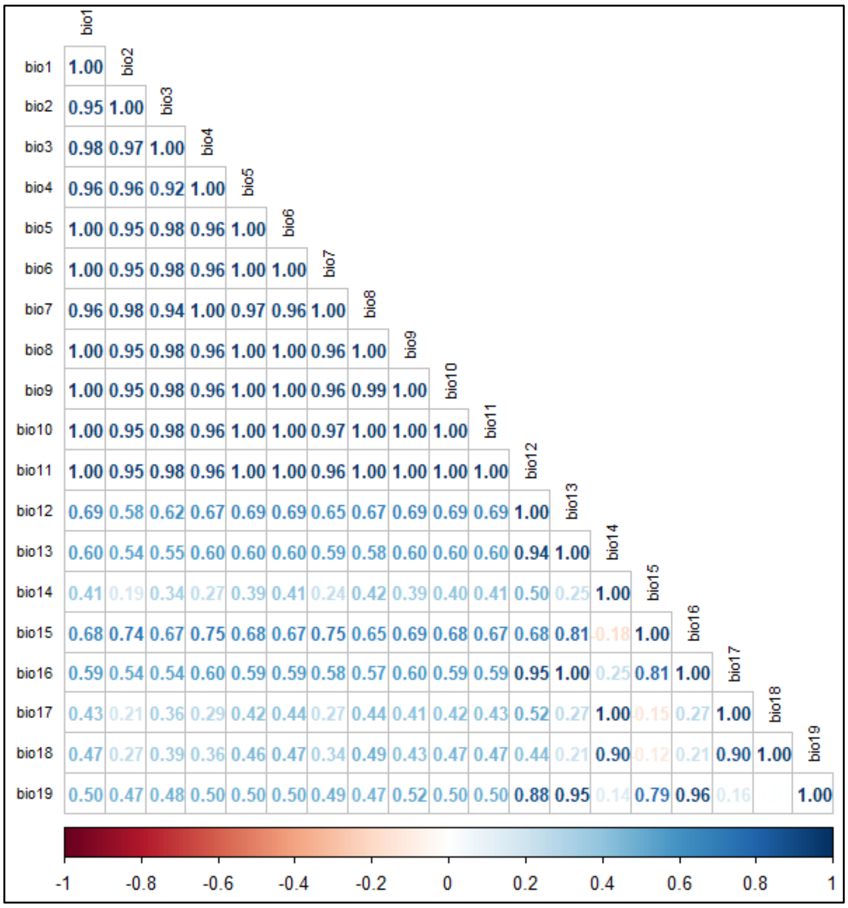
For the current and future distribution modelling of Crimean juniper, the MaxEnt software (version 3.4.4) was employed, incorporating both environmental and climatic variables (Radosavljevic and Anderson, 2014). The MaxEnt modelling approach was chosen due to its ability to deliver the most accurate and reliable results even with a limited amount of presence data, making it superior to other species distribution modelling methods (Warren and Seifert, 2011). But before proceeding with the modelling study, high correlation between bioclimatic variables seriously weakens the reliability and interpretability of the model. In other words, using highly correlated variables together leads to multicollinearity problems, making it difficult to determine which variable is effective in the model and increasing the risk of overfitting. MaxEnt allows examining correlations between variables that may affect plant and wild animal distributions, such as environmental, climate and human factors. Thus, the negative effects of highly correlated variables on the suitability models are eliminated. Therefore, topographic and edaphic variables were used together with bioclimatic data in the modelling phase; possible distribution areas were estimated by establishing a relationship between these variables and the current distribution data of the species (Phillips et al., 2006; Süel, 2014; Ertuğrul et al., 2017; Kaya et al., 2025; Tekeş et al., 2025). To prevent overfitting and ensure the best model performance, cross-validation classification was applied. Additionally, the maximum number of background (bootstrap) points was constrained to 5,000 (Hernández et al., 2025). The default species distribution was utilized, with background point values set to 0.5 in areas lacking environmental and climatic data. In the current modelling of Crimean juniper, 80% of the dataset was designated for training, while the remaining 20% was reserved for testing. The training datasets were utilized to construct the model, while the testing datasets were employed to assess the accuracy of the model. In this regard, the performance of the MaxEnt model was evaluated based on both the training and testing datasets. Specifically, the evaluation of MaxEnt was carried out through the receiver operating characteristic (ROC) curve and the area under the curve (AUC), using values from both the training and test datasets (Elith and Graham, 2009). Among these metrics, area under curve (AUC) is widely accepted due to its effectiveness in evaluating model accuracy as it is not affected by the threshold selection. It has been stated that for the area under curve value, model estimates below < 0.5 (AUC<0.5) are worse than random estimates, values between 0.5 and 0.7 (0.5<AUC<0.7) indicate poor model performance, values between 0.7 and 0.9 (0.7<AUC<0.9) indicate reasonable/good model performance, and values > 0.9 (0.9>AUC) indicate very good performance (Swets, 1988; Baldwin, 2009). Furthermore, the Jackknife analysis of the predicted model should be examined, with particular attention to ensuring that the individual contribution of each variable in this analysis does not surpass its overall contribution to the model. After the variables contributing to the formation of the model are determined in the Jackknife graph, the simulation process should be started (Shcheglovitova and Anderson, 2013). Among the environmental and climatic variables contributing to the target species distribution for the simulation, only the climatic variables need to be adjusted for different years and scenarios (Özdemir, 2018; Özdemir, 2020b; Özdemir, 2024). Because while some future climate changes can be predicted, it is very difficult to obtain clear information about environmental variables (such as floods, avalanches, forest fires, earthquakes). Consequently, the greater the number of climate variables incorporated into the model, the more accurate the predictions regarding the future impacts of global climate change will be.

3. Results and Discussion

3.1. Current distribution modelling and mapping of Crimean juniper

In this study, before starting modelling studies on the potential distribution of Crimean juniper (*Juniperus excelsa*), the correlation between climate variables was examined with the R Studio program to eliminate the problem of multicollinearity between bioclimates (Table 1). After determining that there was a high correlation between the climate variables, factor analysis was applied to reveal the most effective climate variables in the distribution of Crimean juniper. According to the Factor Analysis results, it was determined that 3 components among 19 climate variables explained the model as 98.003% cumulative and 11.365% variance (Table 2). These 3 significant components were found to be bio1 (0.983), bio14 (0.822) and bio19 (0.597), respectively (Table 3).

Table 1. The table showing the multicollinearity problem between the climate variables produced for the study area.



	bio1	bio2	bio3	bio4	bio5	bio6	bio7	bio8	bio9	bio10	bio11	bio12	bio13	bio14	bio15	bio16	bio17	bio18	bio19
bio1	1.00																		
bio2	0.95	1.00																	
bio3	0.98	0.97	1.00																
bio4	0.96	0.96	0.92	1.00															
bio5	1.00	0.95	0.98	0.96	1.00														
bio6	1.00	0.95	0.98	0.96	1.00	1.00													
bio7	0.96	0.98	0.94	1.00	0.97	0.96	1.00												
bio8	1.00	0.95	0.98	0.96	1.00	1.00	0.96	1.00											
bio9	1.00	0.95	0.98	0.96	1.00	1.00	0.96	0.99	1.00										
bio10	1.00	0.95	0.98	0.96	1.00	1.00	0.97	1.00	1.00	1.00									
bio11	1.00	0.95	0.98	0.96	1.00	1.00	0.96	1.00	1.00	1.00	1.00								
bio12	0.69	0.58	0.62	0.67	0.69	0.69	0.65	0.67	0.69	0.69	0.69	1.00							
bio13	0.60	0.54	0.55	0.60	0.60	0.60	0.59	0.58	0.60	0.60	0.60	0.94	1.00						
bio14	0.41	0.19	0.34	0.27	0.39	0.41	0.24	0.42	0.39	0.40	0.41	0.50	0.25	1.00					
bio15	0.68	0.74	0.67	0.75	0.68	0.67	0.75	0.65	0.69	0.68	0.67	0.68	0.81	-0.18	1.00				
bio16	0.59	0.54	0.54	0.60	0.59	0.59	0.58	0.57	0.60	0.59	0.59	0.95	1.00	0.25	0.81	1.00			
bio17	0.43	0.21	0.36	0.29	0.42	0.44	0.27	0.44	0.41	0.42	0.43	0.52	0.27	1.00	-0.15	0.27	1.00		
bio18	0.47	0.27	0.39	0.36	0.46	0.47	0.34	0.49	0.43	0.47	0.47	0.44	0.21	0.90	-0.12	0.21	0.90	1.00	
bio19	0.50	0.47	0.48	0.50	0.50	0.50	0.49	0.47	0.52	0.50	0.50	0.88	0.95	0.14	0.79	0.96	0.16		1.00

Table 2. Factor analysis results applied to bioclimate variables.

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	13.604	71.600	71.600	13.604	71.600	71.600
2	2.857	15.038	86.638	2.857	15.038	86.638
3	2.159	11.365	98.003	2.159	**11.365**	**98.003**
4	0.193	1.016	99.019			
5	0.088	0.462	99.481			
6	0.051	0.270	99.751			
7	0.024	0.127	99.879			
8	0.011	0.058	99.937			
9	0.006	0.033	99.969			
10	0.003	0.015	99.984			
11	0.001	0.006	99.990			
12	0.001	0.004	99.994			
13	0.001	0.003	99.997			
14	0.000	0.002	99.999			
15	0.000	0.001	100.000			
16	0.000	0.000	100.000			
17	0.000	0.000	100.000			
18	0.000	0.000	100.000			
19	0.000	0.000	100.000			

Table 3. Representative variable selection results among bioclimate variables.

Component Matrix			
Variable	**Component**		
	1	**2**	**3**
bio1	**.983**	.065	-.176
bio2	.928	-.125	-.310
bio3	.950	.017	-.244
bio4	.953	-.069	-.210
bio5	.972	.053	-.181
bio6	.952	.070	-.172
bio7	.951	-.084	-.245
bio8	.975	.095	-.193
bio9	.967	.036	-.176
bio10	.961	.059	-.178
bio11	.940	.069	-.174
bio12	.810	-.056	.569
bio13	.736	-.324	.585
bio14	.424	**.822**	.359
bio15	.749	-.633	.087
bio16	.732	-.324	.593
bio17	.449	.808	.361
bio18	.465	.813	.192
bio19	.644	-.442	**.597**

After determining the climate variables that may influence the potential distribution of Crimean juniper, the MaxEnt algorithm, a widely used approach in species distribution modelling, was used. In this section, the accuracy level of the obtained model, the contribution rates of environmental variables to the species distribution, the spatial distribution of suitable habitats and the mapping of model outputs are presented in detail. The findings provide important information about the actual distribution limits of the juniper and are also guiding in terms of conservation of the species and ecosystem management. In this context, to accurately model the current distribution of Crimean juniper, which is native to the Central Anatolian region, a cross-validation classification approach was employed to minimize overfitting and improve model performance. Additionally, the maximum number of background (bootstrap) points was constrained to 5,000 to ensure computational efficiency and model reliability. In areas where there were no environmental and climatic variables, the default species distribution was adopted with 0.5 background point values. The modelling process was repeated until at least two different climate variables remained among the representative variables (Young et al., 2011).

Following the identification of appropriate spatial scales to accurately determine the actual distribution of Crimean juniper within the study area, modelling procedures were initiated. The modelling process continued until at least two distinct variables remained in the final model. According to the results, the average omission rate graph exhibited a low standard deviation (0.0042) (Fig. 2), indicating model stability. The model with this low standard deviation achieved an AUC of 0.866 for the training dataset and 0.792 for the test dataset (Fig. 3). Based on the classification criteria proposed by Baldwin (2009) and Swets (1988), these AUC values indicate that the model performs within the "good" category.

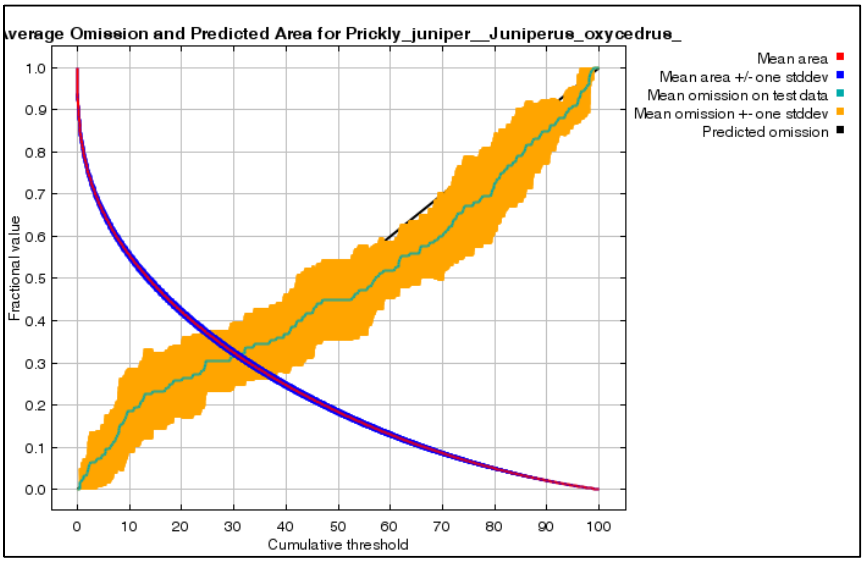


Figure 2. Average Omission graph of the current distribution model of Crimean juniper.

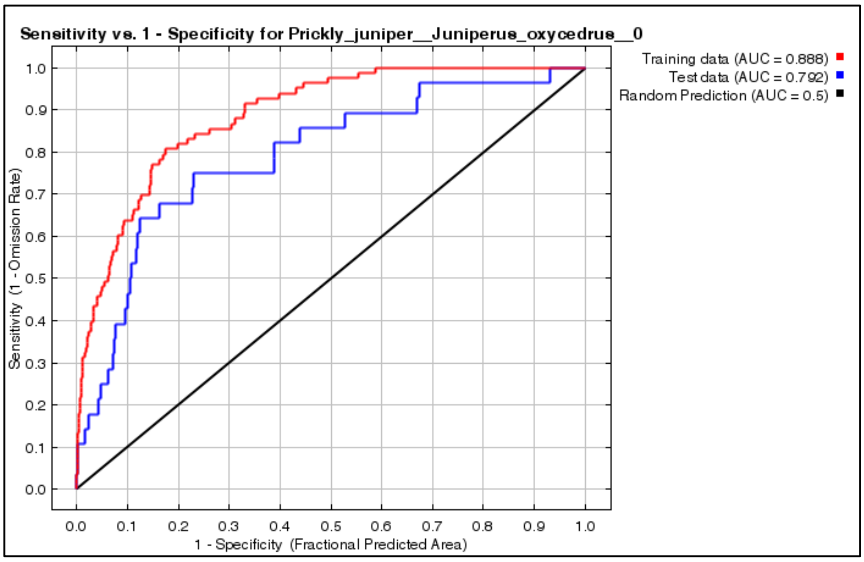


Figure 3. Training dataset AUC and Test dataset AUC of the current distribution model of Crimean juniper.

According to the jackknife results, the variables with the highest individual contributions to the model are, in order: mean annual air temperature (bio1), elevation (ykslti), precipitation of the driest month (bio14), and terrain roughness (rough_3) (Fig. 4).

The permutation importance values for these variables were calculated as follows: mean annual air temperature (bio1: 47.6%), elevation (ykslti: 24.5%), precipitation of the driest month (bio14: 14.1%), and roughness (rough_3: 13.8%).

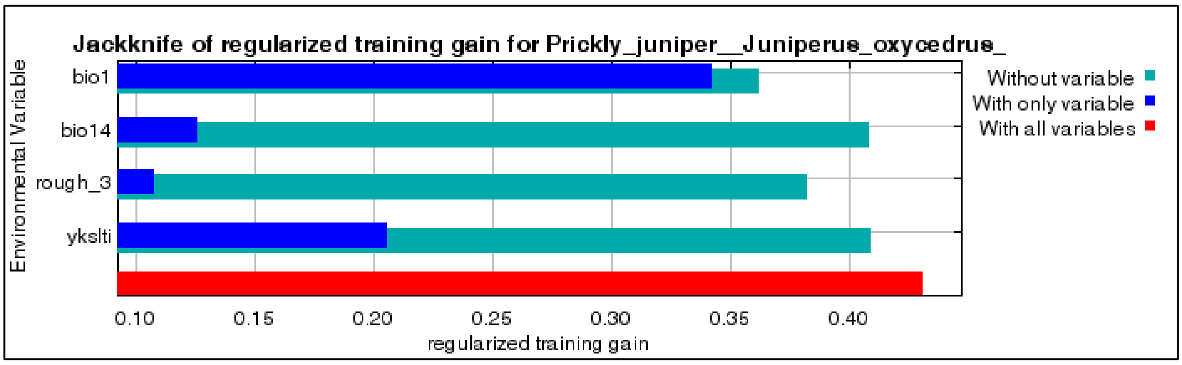


Figure 4. Jackknife graph of the current distribution model of Crimean juniper.

Following the evaluation of the jackknife analysis for the current distribution model of Crimean juniper, it is essential to examine the marginal response curves of the environmental and climatic variables contributing to the model. In this context, the variables that significantly influence the model are bio1 and bio14. Among these, mean annual air temperature (bio1) emerged as the most influential variable. According to the model, areas with mean annual temperatures between 28.2°C and 28.6°C (Fig. 5A), and with precipitation levels in the driest month ranging from 0 mm to 500 mm (Fig. 5C), exhibit a high probability of Crimean juniper occurrence. Bioclimatic variables such as temperature and precipitation are known to play a critical role in the distribution and ecological health of Crimean juniper (Adams et al., 2014; Özkan et al., 2010b; Özdemir et al., 2020a). This species typically thrives in regions characterized by a Mediterranean climate, with hot, dry summers and mild, wet winters. In this context, precipitation patterns and soil moisture availability are critical determinants of its growth and distribution (Cano-Ortíz et al., 2018). The relationship between these climatic variables and Crimean juniper is further complicated by local geomorphological features that can create microclimates that favour or inhibit its growth (Cano-Ortíz et al., 2021). Crimean juniper habitat selection is shaped by the annual thermal and precipitation regimes that define its bioclimatic envelope. High temperatures combined with limited precipitation in the driest month may create challenges related to water stress, affecting seed germination and plant health (Herrero and Zamora, 2014). Therefore, understanding specific thresholds for these bioclimatic variables aligns with the literature on habitat preferences and potential changes in distribution due to climate change.

Among the environmental variables contributing to the formation of the current distribution model of Crimean juniper, elevation and terrain roughness index were identified as significant. According to the marginal response curves, the species is most likely to occur at elevations between 800 and 1500 meters (Fig. 5B), and the probability of occurrence increases with higher roughness index values (Fig. 5D). Elevation is recognized as a key factor influencing microclimatic conditions that affect the distribution of Crimean juniper. The species is known to thrive at altitudes up to approximately 1600 meters above sea level and is frequently found on rocky terrains (Tundis et al., 2020; Cano-Ortíz et al., 2021). Additionally, it has been reported that Crimean juniper is distributed locally at elevations between 1000 and 1300 meters in colder zones of the Taurus Mountains in the Mediterranean region, as well as on the Central Anatolian plateau (Özkan et al., 2015; Özdemir et al., 2020a). As elevation increases, temperature fluctuations increase, creating environmental stress factors that force it to adapt more. In other words, high elevation causes lower growth rates due to physiological limitations resulting from lower temperatures and possible water restrictions during critical growth stages (Kutbay and Ok, 2003; Dakhil et al., 2021). Based on the roughness index variable, it has been suggested that Juniperus species exhibit a high resistance to cavitation, a critical trait for maintaining water transport under arid environmental conditions (Willson et al., 2008). This feature allows Crimean juniper to thrive in areas with surface irregularities and fluctuating water availability. Crimean juniper contributes to shrub invasion in meadows, which can affect biodiversity and habitat suitability. These encroachment dynamics, encouraged by the structural complexity of the habitat, allow Juniper excelsa to thrive while also changing the substrate species composition (Ninot et al., 2024).

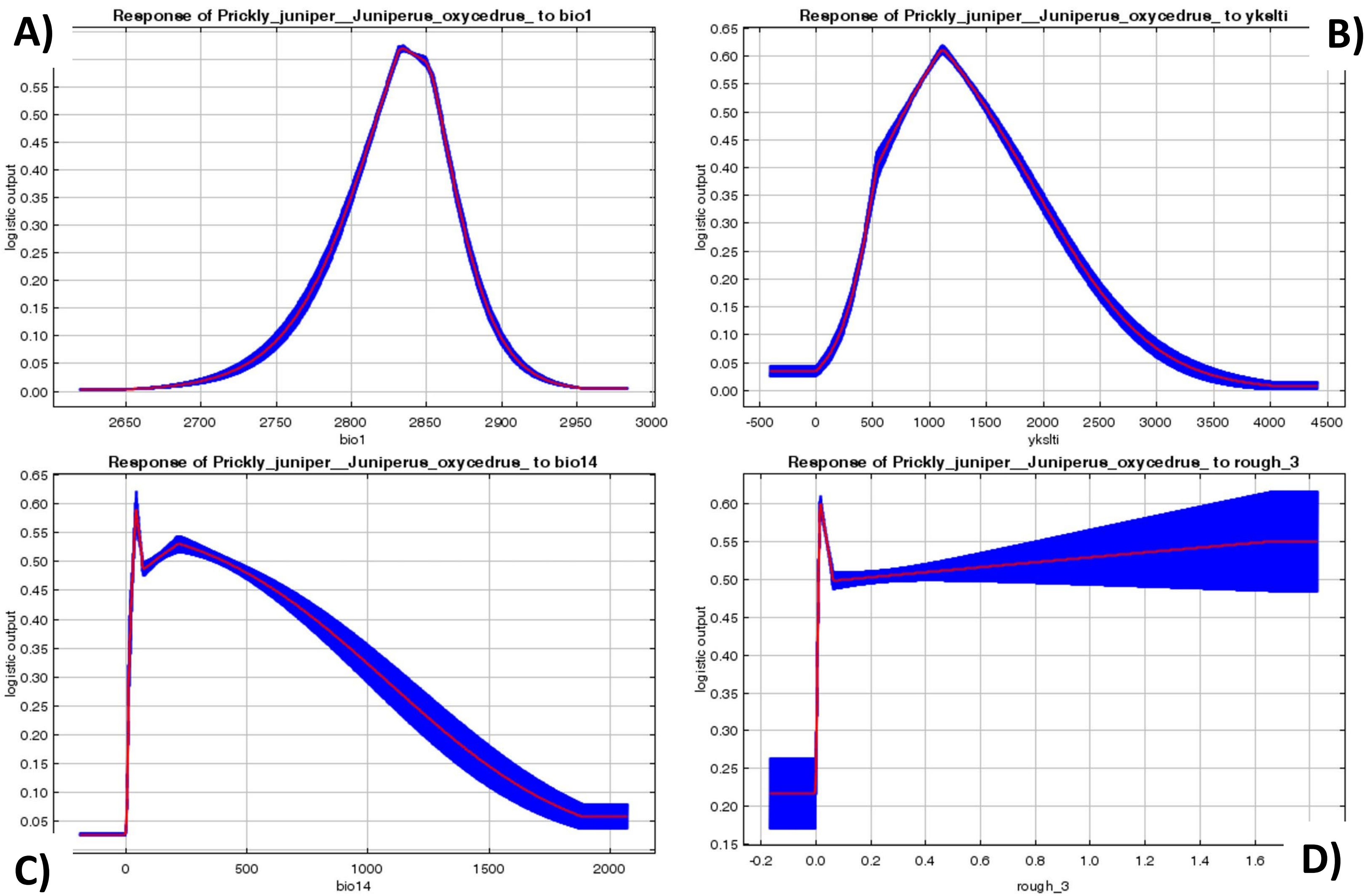


Figure 5. Marginal graphs of variables contributing to the current model of the Crimean Juniper: A) mean annual air temperature graph B) elevation graph, C) precipitation amount of the driest month graph and D) roughness index graph.

This study aims to identify the potential distribution areas of Crimean juniper (Juniperus excelsa) under both current and future climatic conditions, in line with previous research (Özcan et al., 2023). To this end, a current distribution model for Crimean juniper in the Central Anatolian region of Türkiye was developed, and the environmental variables contributing to the model were identified. Based on 198 presence records and the values of variables influencing the species' distribution, a current distribution map was generated using the MaxEnt modelling approach (Fig. 6). The results indicated that areas characterized by specific elevation ranges and terrain roughness were suitable for the species' distribution. These suitable habitats were primarily concentrated in the northern parts of the study area and in the southeastern section near the Mediterranean region. In contrast, the Salt Lake and its surrounding areas, located in the central part of the study region, were identified as unsuitable for the presence of Crimean juniper.

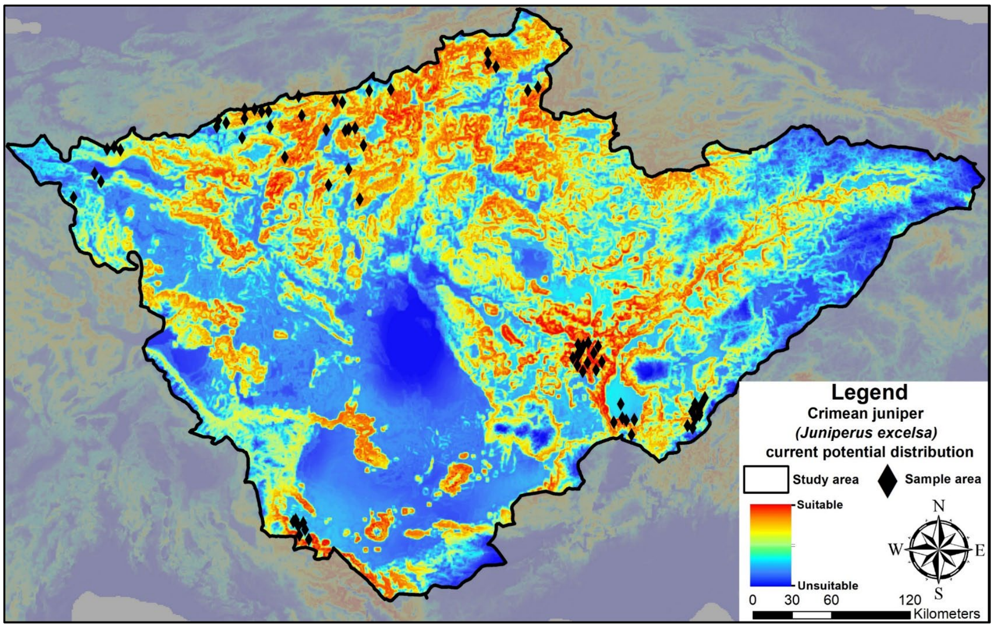


Figure 6. Current distribution mapping of Crimean juniper.

3.2. Spatiotemporal mapping of Crimean juniper distribution under different climate scenarios and time periods

Using the variables contributing to the current distribution model of Crimean juniper, climate projections for the years 2070 and 2100 were simulated under the Chelsa SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. The simulation results indicated a significant fragmentation of the species' distribution in the 2070 scenarios (Fig. 7). By 2100, under the various climate scenarios, the results suggested that Crimean juniper's distribution in the Central Anatolian region is at a substantial risk of extinction (Fig. 8). In this context, the MaxEnt method revealed significant changes in the geographical range of Crimean juniper under future climate scenarios and emphasized the need for urgent conservation efforts (Fatemi et al., 2018). However, it has been shown that the growth of the decimated juniper can vary in response to rising temperatures and may be more resilient than other tree species that show more pronounced climatic stress responses (Seim et al., 2016). However, this resilient complicates conservation efforts as the species may be vulnerable in the long term, despite not currently showing immediate stress-related symptoms. Dakhil et al. (2021) stated that the interaction of climate change and other environmental factors such as land use and competition is exacerbating the challenges faced by junipers, including Crimean juniper. As a result, the Crimean juniper simulation and mapping results are in the same direction as the literature studies.

After the simulation maps of the Crimean juniper are produced, quantitative metrics such as the total area of suitable habitat (%), patch number/size and area ratios according to suitability class are needed to reveal the decreases or shifts in the distribution of the Crimean juniper according to these simulations (Kaya et al., 2025). In this context, the current and potential distribution maps of the Crimean juniper predicted by the MaxEnt method are categorized (%) as unsuitable, low suitability, medium suitability, and high suitability. These categorization degrees are 0.0-0.5 as unsuitable, 0.51-0.70 as low, 0.71-0.90 as medium and 0.91-1.00 as high suitability areas. In this category, the areas shown in grey are unsuitable areas, low suitability areas are mapped in orange, medium suitability areas are mapped in yellow and very suitable areas are mapped in red. Based on these colourings, it has been determined that 30.4% of the current distribution of Crimean juniper in the Central Anatolia region is suitable areas, 31.3% is medium suitability areas, 26.7% is low suitability areas and 11.6% is unsuitable areas (Fig 9).

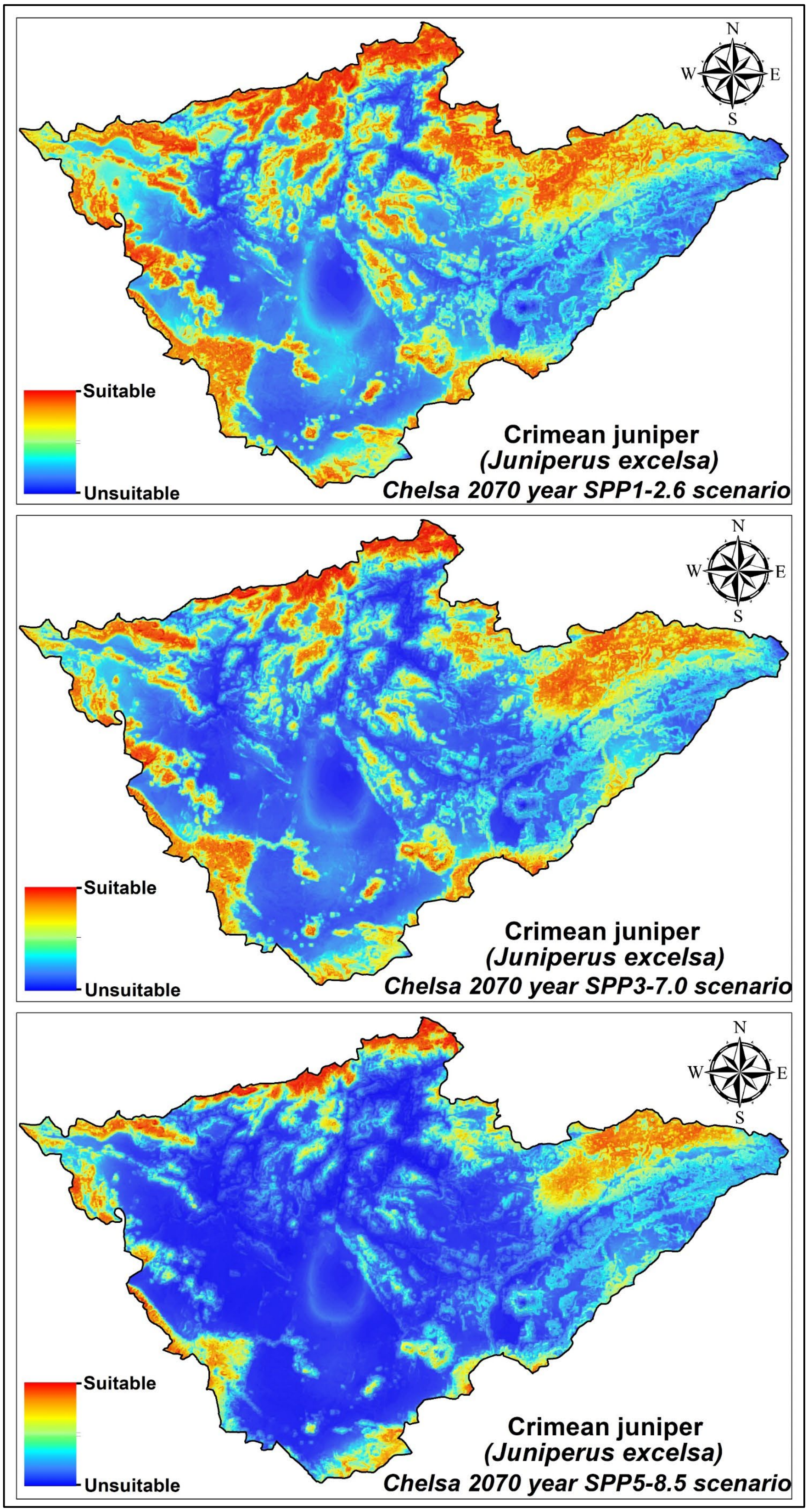


Figure 7. Simulation of Crimean juniper according to Chelsa SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios between 2070.

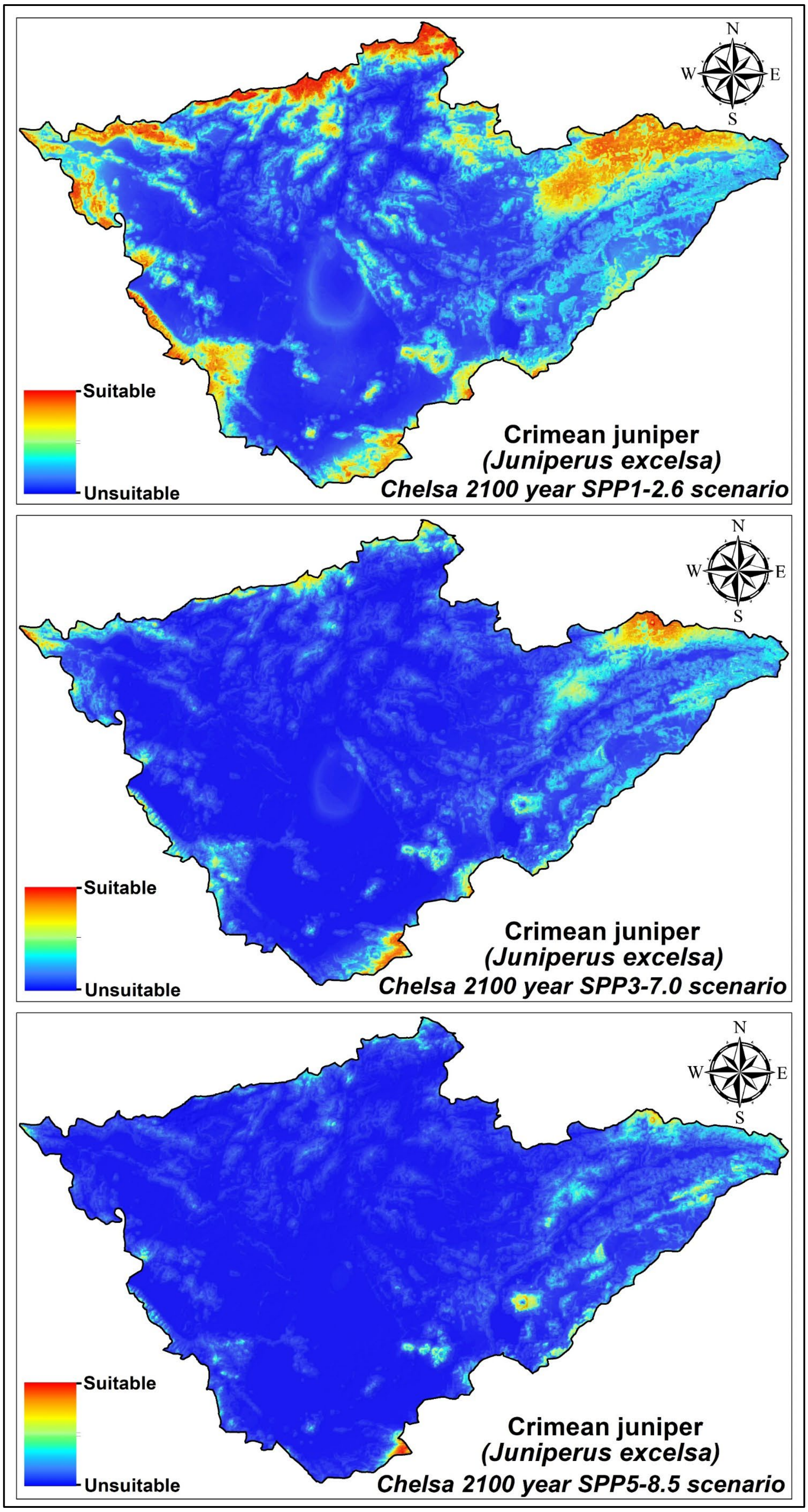


Figure 8. Simulation of Crimean juniper according to Chelsa SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios between 2100.

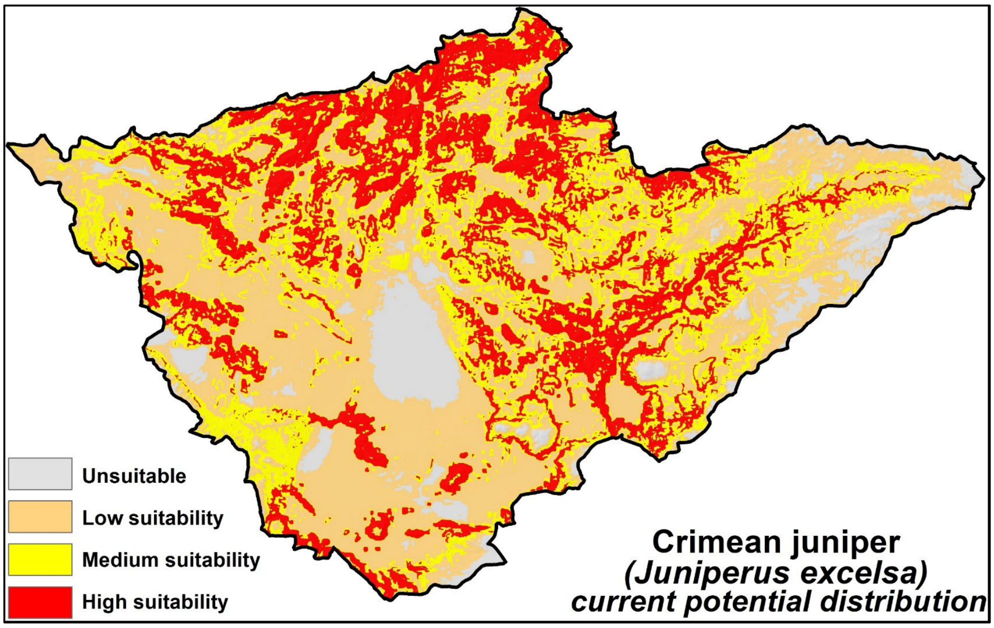


Figure 9. Classification of unsuitable, low, medium and high suitability areas of the current distribution of the Crimean juniper

After the suitability classification of the current distribution of the Crimean juniper was determined, the determination of the suitability areas in the maps prepared according to different scenarios for the years 2070 (Fig 10) and 2100 (Fig 11) was started. The same classification degree and colouring were used for different years (2070-2100) and scenarios (SSP1-2.6, SSP3-7.0, SSP5-8.5). In this context, the obtained unsuitable, low, medium and high suitability area rates are presented in Table 4.

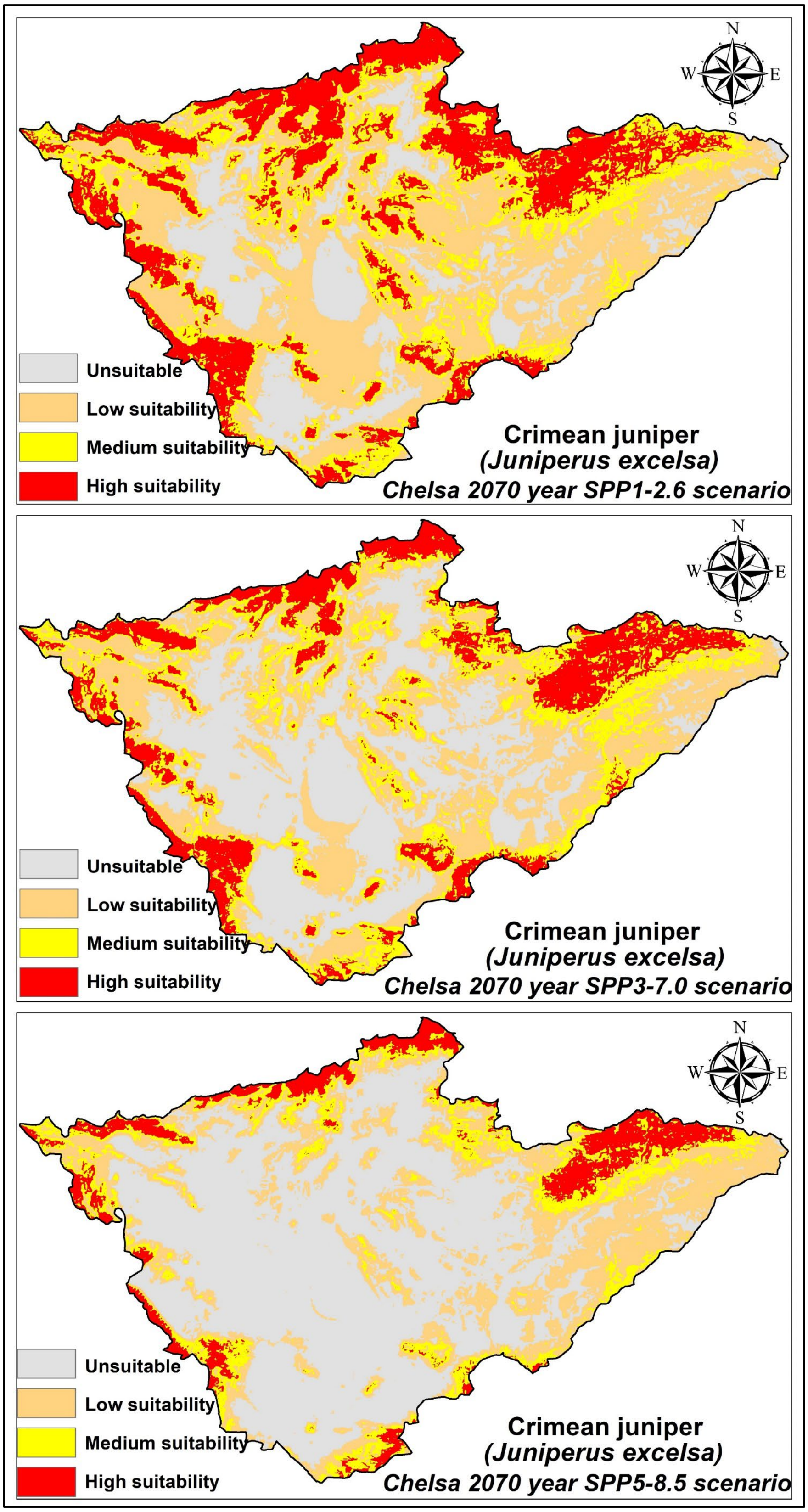


Figure 10. Classification of SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios for the year 2070 as unsuitable, low, medium and high suitability areas.

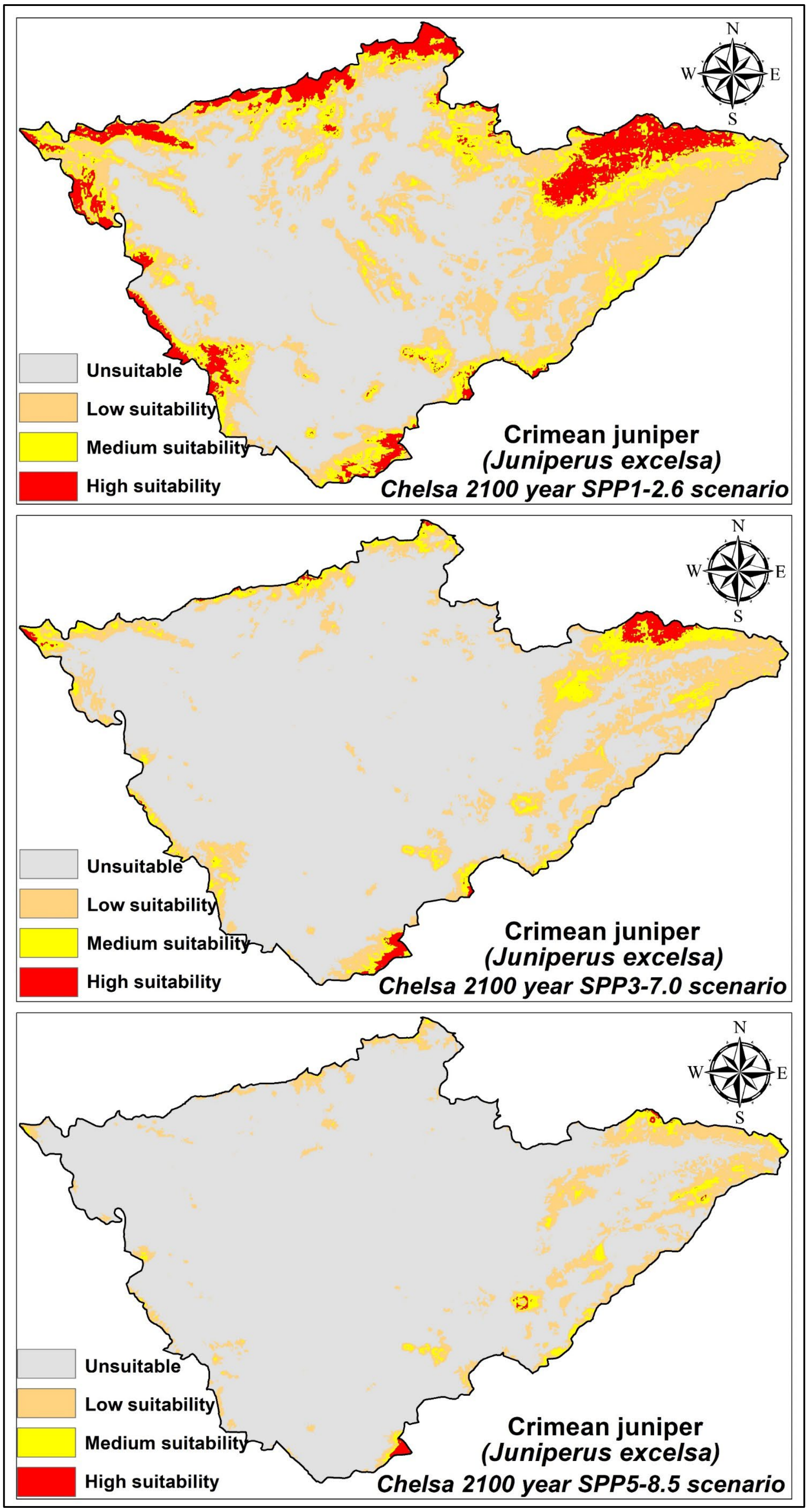
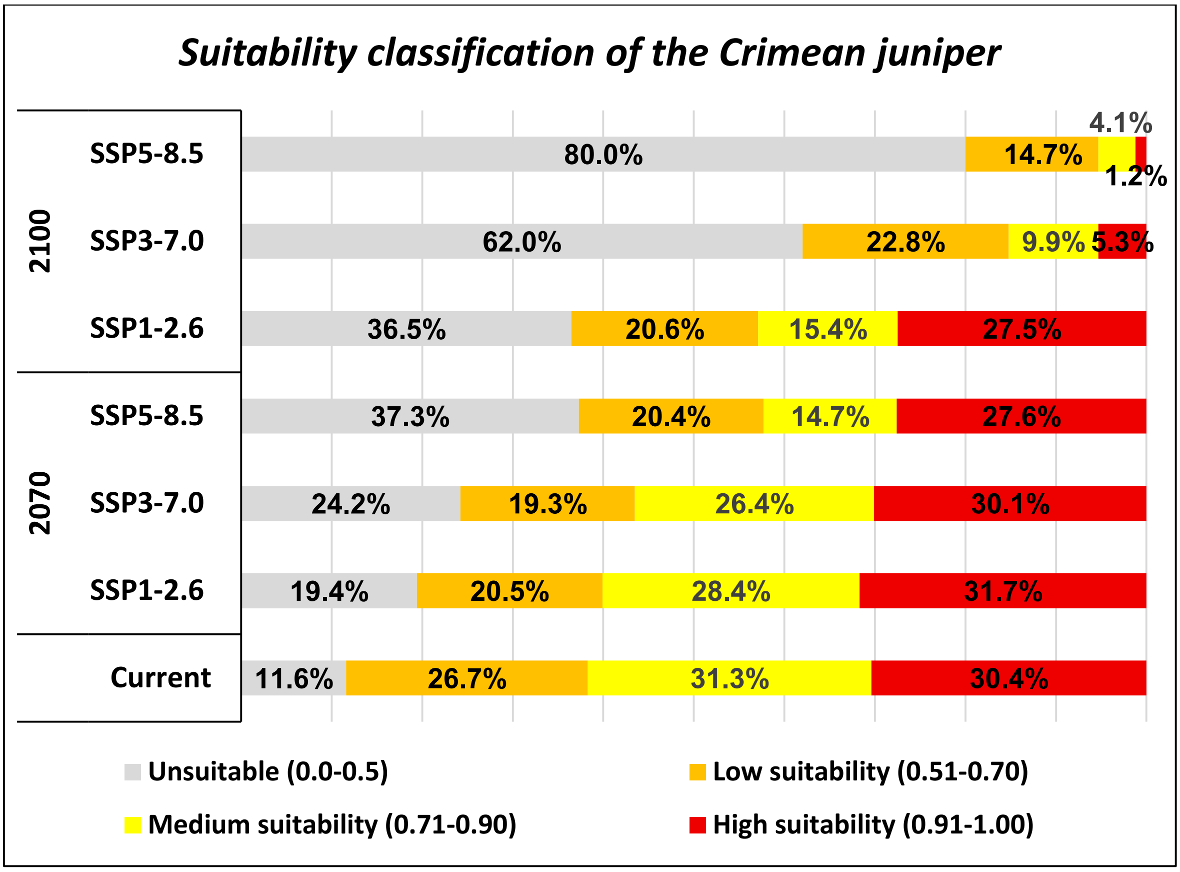


Figure 11. Classification of SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios for the year 2100 as unsuitable, low, medium and high suitability areas.

Table 4. Suitability classification of the Crimean juniper.



According to Table 4, it was determined that 11.6% of the Crimean juniper is unsuitable for current distribution. When this situation is evaluated according to 2070, 19.4% in the SSP1-2.6 scenario, 24.2% in the SSP3-7.0 scenario and 37.3% in the SSP3-8.5 scenario were determined as unsuitable areas. Therefore, in any scenario for 2070, the increase in unsuitable areas for Crimean juniper is a prediction that the species distribution will decrease or fragment. According to the Chelsea climate scenarios for the year 2100, it was determined that it was 36.5% in the SSP1-2.6 scenario, 62.0% in the SSP3-7.0 scenario and 80.0% in the SSP3-8.5 scenario. Therefore, any scenario for the year 2100 reveals that the areas unsuitable for juniper will increase significantly and the distribution of the species will almost disappear. As a result, this study has revealed the ecological fragmentation and extinction process of the Crimean juniper distributed in Central Anatolia under the influence of global climate change.

4. Conclusion

This study highlights the dependence of Crimean juniper distribution on certain climatic parameters (e.g. mean annual temperature, dry month precipitation) that may become increasingly unpredictable under climate change conditions. It is suggested that Crimean juniper needs potential distribution and adaptive management strategies that consider possible climatic changes. In the face of these unprecedented changes, conservation strategies (e.g. habitat restoration, ex situ conservation, monitoring programs) are emphasized to reduce these impacts and preserve this vital species for future generations. It is also recommended that model results be included in species protection action plans or forest planning so that the Crimean juniper can survive global climate change with minimal damage. In conclusion, this study provides evidence that can support decision-makers (forest management, protected areas, local governments, etc.) by revealing the silent ecological response of Crimean juniper to global climate change.

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