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Assessing Climate Change Impact on Habitat Suitability and Ecological Connectivity of Wych Elm (*Ulmus glabra* Huds.) in Türkiye

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Abstract: Understanding how climate change influences the geographical distribution of species within an ecological niche is essential for predicting habitat shifts and informing conservation efforts. This study evaluates the impact of climate change on habitat suitability and ecological connectivity of wych elm (*Ulmus glabra* Huds.) in Türkiye. The study explores the future distribution of *U. glabra* and how its connectivity is affected by habitat fragmentation arising from changing climatic conditions. Contextually, this paper aims to achieve two primary objectives: estimating the potential geographical ranges of *U. glabra* under different climate scenarios and assessing alterations in ecological connections between current and future habitats. The maximum entropy (MaxEnt) model was used along with Morphological Spatial Pattern Analysis (MSPA), and the Probability of Connectivity (PC) index was applied to show possible transformations in distribution patterns of *U. glabra* over time. The findings suggest that there will be a reduction in the suitability of locations for the species. Moreover, it is expected that under future climate scenarios, ecological connectivity will decline, especially from 2061 to 2100 in the SSP585 scenario. Notably, significant alterations are anticipated during the latter half of the twenty-first century, mainly outside the coastal areas of the Black Sea, where extensive regions would become unsuitable. Additionally, the species is projected to shift its range, decreasing its presence in inland regions while expanding along the coasts. The results show the vulnerability of this species against climate change, thereby demanding adaptive conservation measures to preserve it within the forest ecosystems of Türkiye.

Keywords: ecological niche modeling; maximum entropy; habitat fragmentation; conservation; forest ecosystems; climate scenarios

1. Introduction

Climate change significantly threatens Earth and its biodiversity [1–3]. Shifts in atmospheric composition have profound effects on species distributions, ecosystems, ecological processes, and human life [4–7]. The current increase in the Earth’s temperature is about 1 °C above pre-industrial levels (0.8 °C–1.2 °C) [8]. If this trend continues without effective measures to mitigate global warming, it is projected that between 2030 and 2052, the temperature could be raised by approximately 1.5–2 °C [9,10]. The anticipated temperature increase could intensify the frequency of natural disasters and further strain vulnerable ecosystems.

Global forest ecosystems are significantly affected by climate change [11–13]. Research has shown that there is an alteration in forest ecosystems due to shifting conditions such as rainfall pattern changes, increased fire incidences, and shifts in species distribution ranges, as well as changes in vegetation type, phenology, and reproductive biology of the plants [14–16]. These changes negatively affect the distribution pattern of trees, insects, and pathogens in most areas, and an increase in pests is expected as a result [17]. Also, climate change affects forest biodiversity, ecosystem functioning, and resilience, possibly resulting in species diversity shifts or potential loss in plant diversity [18,19]. Climate change has recently resulted in significant disturbances within forests, resulting in habitat heterogeneity that promotes diversification and regeneration or reorganization of ecosystems [20,21]. The impact on these ecosystems will likely worsen over time and eventually lead to irreversible changes involving non-forest land cover types, either temporary or permanent [22]. To tackle climate change regarding the sequestration of carbon dioxide and mitigation measures entails the preservation, sustainable management, and rehabilitation of forests [23,24]. In addition, forests represent significant reservoirs of carbon stocks and terrestrial biodiversity, emphasizing the need to comprehend and mitigate the effects of climate change on forest ecosystems [25].

Conservation practices have been adopted to lessen the adverse effects of climate change on habitats and biodiversity [26]. One of these is enhancing ecological connectivity [27,28]. Connectivity in the landscape denotes the interaction and coordination among landscape elements [29]. Tischendorf and Fahrig [30] argue that connectivity plays an important role in ecological processes as well as the survival of living organisms. Furthermore, it serves as the primary form of communication between individuals within communities and the broader landscape [31]. Connectivity between habitats can arise over long or short periods, and habitats may experience isolation at a similar rate [32]. Increased habitat connectivity promotes dispersal and reduces population declines, allowing endangered populations to expand in a balanced way [33,34]. Thus, conservation strategies must be developed to prevent biodiversity loss [35,36]. As the connectivity between habitat patches increases, the mobility of species within the landscape will improve, thereby reducing the isolation effect caused by habitat fragmentation [27,37,38].

Several recent studies utilizing species distribution modeling (SDM) have shown the different effects of climate change on tree species, emphasizing that specific responses to environmental shifts by species result in changes in distribution patterns based on their characteristics and adaptabilities [39–42]. Combining these changes in distribution patterns with SDMs that utilize species occurrence data to examine how they may adapt to changing climatic circumstances can help predict the suitability of habitats using environmental information [43,44]. As one of the machine learning techniques, maximum entropy (MaxEnt) is widely used for SDM because it can generate robust predictions even from limited data and is, therefore, an effective tool for modeling species distribution [45,46]. The MaxEnt model depends on presence-only data and determines the distribution of

maximum entropy using environmental variables [46]. Previous studies have shown that climate change affects tree species differently; some exhibit niche contraction [47–51], while others indicate niche expansion [52–54]. Specifically, future climate scenarios will significantly decrease in *Picea abies* L., *Abies alba* Mill., and *Fagus sylvatica* L. suitable habitat as indicated by SDM analysis, which reflects its ecological niche contraction [55]. However, expected variations in temperature and precipitation may broaden the range of *Robinia pseudoacacia* L. and make it more suitable in Northern, Western, and Eastern Europe. In order to manage forest ecosystems effectively, different responses must be understood, and specific conservation strategies must be designed for different tree species depending on their projected future distributions.

Species distribution is influenced by environmental variables, biotic interactions, and species-specific traits, including dispersal ability and evolutionary history [56]. While environmental factors like climate and habitat availability form the basis for niche establishment, biotic factors such as competition, predation, and symbiotic relationships further shape distribution patterns. The evolutionary trajectory of a species plays a pivotal role, as historical adaptations and phylogenetic constraints influence its ecological niche and capacity to respond to current environmental pressures [57,58]. Therefore, understanding species distributions requires an integrated approach that considers abiotic factors and the complex dynamics of biotic interactions and evolutionary legacies, which govern species persistence and spatial patterns. The present study aims to answer the following questions: (1) What is the potential geographic distribution of *Ulmus glabra* under different climate change scenarios in the present and future? (2) How will ecological connectivity between current and future potential habitats of *U. glabra* change under different climate scenarios? Thus, this paper will assess changes in spatial units that provide connectivity in potential and future distributions of species through the MaxEnt model [46], Morphological Spatial Pattern Analysis (MSPA) [59], and Probability of Connectivity (PC) index [60]. The novelty of this research lies in integrating an ecological connectivity approach with SDM and analysis of the trade-off between morphological units. As such, a sample methodology is provided to show how potential corridors' spatial and temporal changes in potential corridors can be analyzed both in the present and the future. Hence, this research provides a detailed overview of sustainable development for Türkiye's silviculture by conserving *U. glabra* and suggests robust management strategies. Moreover, it is further discussed how this information can be used as a framework for translating theory into practice while managing forest species at a landscape scale.

2. Material and Methods

2.1. Target Species and Occurrence Data

Ulmus glabra Huds., a tree of the family Ulmaceae, is an ecologically and economically important species that thrives in temperate, humid climate conditions. It may grow up to 20 m tall with a dense crown [61]. The bark is smooth, gray-brown when young, with thick, pendant branches. This species does not produce root suckers like some other elms [62]. The leaves are rough, asymmetrical, serrated, and dark green; they have very short petioles; the leaf surface is hairy. They are larger than those of most trees—about 5–17 cm long and 4–12 cm wide. The flowers are brown-purple and appear before the leaves. They are bell-shaped hermaphroditic wind-pollinated flowers [63]. Seeds are located in center of a papery wing; fruits are clustered green balls about 2.5 cm across [64,65]. It can form mixed forests with other broad-leaved species that share similar habitat and climate requirements, such as *Fraxinus* spp. (ash), *Acer* spp. (maple), *Tilia* spp. (linden), *Populus* spp. (poplar), *Salix* spp. (willow), *Quercus* spp. (oak), and *Alnus* spp. (alder) [64,65].

Martin del Puerto et al. [66] identify human intervention, climate change, and factors such as Dutch elm disease as the main threats to *U. glabra* populations. The presence of *Ceratocystis ulmi* is a significant threat to the distribution of *U. glabra* in Türkiye; this pathogen causes Dutch elm disease that results in severe wilting and mortality among elms [67,68]. This is triggered by environmental conditions like droughts, which disrupt

the species' ability to thrive in affected areas [68,69]. It becomes imperative, therefore, that the species must be monitored, and its response to changing climatic conditions needs to be understood.

Occurrence data for the studied species were prepared based on open access sources and the relevant literature. The data were spatially thinned to 5 km to prevent spatial autocorrelation and to ensure evaluation at the same scale as bioclimatic variables. In the modeling stage, 402 occurrence records were used [61,70–72]. The study area covers the boundary of Türkiye (Figure 1). The current distribution of *U. glabra* in Türkiye is fragmented into different regions: western part of Marmara Region, southern slopes of Black Sea, Eastern Black Sea mountains chain, Eastern Anatolia, southern slopes of Western and Central Taurus Mountains, Central Anatolia and Aegean Region. It is especially abundant on the eastern part of Black Sea coast extending westwards from Georgian border.

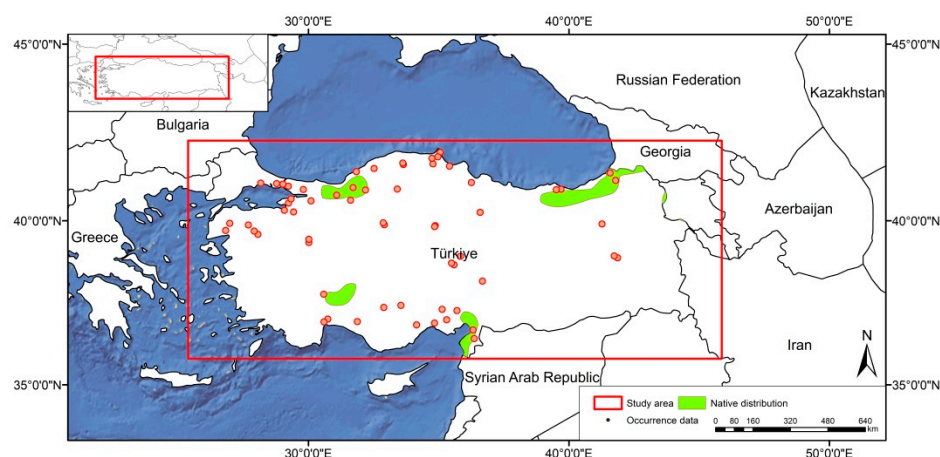


Figure 1. Study area with native species distribution and documented occurrence data.

2.2. Environmental Data

Climate data were obtained from the WorldClim v2.1 database [73] with a spatial resolution of 2.5' (approximately 4.7 km). It is important to note that the variables used in WorldClim are derived from monthly temperature and rainfall data for every month between 1970 and 2000. We used 15 bioclimatic variables (Table A1), excluding 4 variables (BIO8, BIO9, BIO18, and BIO19) due to known spatial artifacts in previous studies (i.e., [69,70]).

To mitigate the adverse effects of multicollinearity and high correlation among bioclimatic variables [74,75], we excluded those having a variance inflation factor less than 10 and using a correlation threshold of 0.75 as suggested by Guisan et al. [76]; this was achieved via the “usdm” package [77]. We selected six bioclimatic variables as predictors based on species ecological requirements: BIO2 (Mean Diurnal Range), BIO3 (isothermality), BIO5 (Maximum Temperature of Warmest Month), BIO12 (annual precipitation), BIO14 (Precipitation of Driest Month), and BIO15 (Precipitation Seasonality, Coefficient of Variation).

For future habitat suitability assessment, we projected fitted models under five different Global Climate Models (GCMs) viz., BCC-CSM2-MR [78], CNRM-CM6-1 [79], CNRM-ESM2-1 [80], CanESM5 [81], and MIROC6 [82] to account a reasonable uncertainty in climate model projections as recommended by Sanderson et al. [83]. The future datasets were obtained for four periods, namely 2021–2040, 2041–2060, 2061–2080, and 2081–2100 from CMIP6 (www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6 accessed on 10 November 2023), sixth Climate Model Intercomparison Project, with three shared socioeconomic pathways, i.e., optimistic (SSP245), middle of the road (SSP370), and pessimistic scenario (SSP585).

2.3. Species Distribution Modeling (SDM)

Habitat suitability prediction for current as well as future potential geographical distribution of *U. glabra* across the entire study area was performed using species distribution models (SDMs)—MaxEnt algorithm [84]. So, to calibrate SDMs, R package “kuenm” in the R v3.6.3 environment was used to create different MaxEnt models under varying parameter setting combinations [85]. In R v4.3.1 environment, several candidate models were generated according to different combinations of parameter settings, each model being associated with different environmental variables and feature classes: 10 regularization multiplier values (0.1, 0.5, 1, 1.5, 2, 3, 4, 5, 8, and 10) [86], and 5 combinations of feature classes (l, lq, lqp, lqpt, and lqpth where l = linear; q = quadratic; p = product; t = threshold; h = hinge). Thereby, model performance assessment involved significance, which was evaluated through partial Receiver Operating Characteristic (ROCs) up to 500 iterations with bootstrapping at 50% data omission rates $\leq 5\%$ omitted for complexity. The iterations were adjusted using $AICc < 2$ final models [87] selected parameters complete set occurrences bootstrap ten replicates cloglog outputs background points ten thousand. The ensemble method was used to apply the models in the study area for current and future scenarios. For the final estimation, partial ROC calculation and omission rate were calculated using an independent dataset. The species distribution results were derived from the median of all replicates. The habitat suitability was represented on a scale of 0 (unsuitable) to 1 (suitable). The logistic threshold of training presence of 10 percentile as proposed by Liu et al. [88], was used to convert maps, which were visualized with RasterVis package [89].

2.4. Morphological Spatial Pattern Analysis (MSPA)

GuidosToolbox software (v. 3.1), a versatile platform that estimates habitat composition, connectivity, and fragmentation independent of species-specific responses was used in conducting a suite of analyses based on habitat connectivity [90]. Morphological Spatial Pattern Analysis (MSPA) is a set of customized mathematical morphological operators to describe the geometry and connectivity of image components [91,92]. This method can be applied to any type of digital image at any scale in any application domain based on geometric concepts only [93]. MSPA works with binary data structures. Seven pattern classes are created by the morphological structure derived from MSPA [91]: ‘core’, which refers to interior area excluding edge; ‘islet’, referring to small isolated areas; ‘loop’, representing areas connected to same core; ‘bridge’, showing those connected between different core areas; ‘perforation’, meaning areas surrounding interior objects; ‘edge’, showing areas surrounding exterior objects; ‘branch’, indicating regions connected with edge, perforation, bridge or loop. These seven classes are important indicators for detecting fragmentation and loss of habitats in forest-dominated landscapes. For example, within forests, core areas are more continuous than fragmented, while edges show where boundaries formed after perforation has occurred; thus, invasive or boundary-dependent species will tend to occur more frequently at edges than in cores.

Connecting bridges represent potential movement paths for species and areas where ecological sensitivity may be caused by fragmentation. Branches act as potential corridors (bridges) between core areas. In some cases, different combinations of these classes can be used during interpretation, but their meanings remain constant throughout all the configurations created during analysis, i.e., three types of branches forming bridges may indicate fragmented or disconnected connectivity [59]. MSPA segmentation results in 25 feature classes, which, when combined, correspond exactly with the initial foreground area. Since most forests undergo edge effects within 0–5 m (or 2 pixels) from an edge, MSPA sets edge width as 3 m [94]. In previous studies, connectivity analyses have focused mainly on bridge and core classes due to their direct role in spatial connectivity [94,95].

2.5. Probability of Connectivity Index (PC)

The PC (Probability of Connectivity) index is used to assess functional connectivity based on habitat suitability, dispersal probabilities, and graph structures [60]. Additionally,

the PC index is a part of network analyses and enables the measurement of habitat loss and landscape fragmentation [95]. MSPA is used as input in network analysis for calculating the PC index. Network analysis directly evaluates core areas resulting from MSPA, referred to as 'nodes', and corridors, i.e., 'links'. Both nodes and links are collectively referred to as 'components'. Network analysis has two significant outputs: components (network components) and node/link importance. In component analysis, the components representing different units of the network are calculated. The Equivalent Connected (node/core) Area (ECA) is calculated as the square root of the following formula:

$$PCnum = \sum_{i=1}^N (node\ area_i)^2 \quad (1)$$

In the formula, $PCnum$ represents the number of connectivity probabilities (total number of existing habitats) as introduced in the ecological connectivity concept by Saura et al. [91]. ECA_rel is the normalized or relative ECA value and is calculated with the following formula:

$$ECAmax = \sum_{i=1}^N (node\ area_i) \quad (2)$$

In landscape habitat studies, ECA_rel is also known as the amount of reachable habitat. ECA_rel is equivalent to the degree of network connectivity of the network components in the image. Node/link importance, proposed by Saura and Pascual-Hortal [60], is essentially the sum of three important variables:

$$dPC = dPCintra + dPCflux + dPCconnector \quad (3)$$

In the formula, dPC indicates the importance degree of accessibility to habitats in a landscape; $dPCintra$ represents intrapatch connectivity, and $dPCconnector$ represents the contribution of a patch or link to the connectivity between other habitat patches. Among these three variables, only $dPCconnector$ has been used to map node and link importance.

3. Results

3.1. Model Selection and Estimation Results

As a result of examining the variance inflation factor (VIF) values of bioclimatic variables, it was found that 8 out of 15 bioclimatic variables had multicollinearity issues. After removing the highly correlated variables, the minimum linear correlation was -0.005 (BIO4~BIO1), and the maximum linear correlation was -0.73 (BIO15~BIO14). A total of six variables were used in the modeling. The selected variables are annual mean temperature (BIO1, VIF = 2.23), isothermality (BIO3, VIF = 1.78), temperature seasonality (BIO4, VIF = 2.23), annual precipitation (BIO12, VIF = 3.10), precipitation of the driest month (BIO14, VIF = 5.98), and precipitation seasonality (BIO15, VIF = 6.32). In total, 350 candidate models were evaluated, with parameters reflecting all combinations of 10 regularization multiplier settings, five feature class combinations, and seven distinct sets of environmental variables.

The performance of candidate models was evaluated in terms of statistical significance (partial ROC < 0.05), good performance (%5 OR = 0.058), and low complexity (AICc = 7990.84). According to these statistics, the model with a delta AICc value of 0 was selected as the final model (M_1.5_F_lqpt_Set_4). The results indicate that the habitat suitability of the species is explained by annual precipitation (BIO12, 31.9%), seasonal temperature (standard deviation max100) (BIO4, 31.8%), precipitation of the driest month (BIO15, 24%), annual mean temperature (BIO1, 8.5%), and isothermality (BIO3, 3.7%). For the performance of the model, we used the Area Under the Curve (AUC) value from the ROC analysis where it had an AUC value of 0.889 and 0.823 for training and test data, respectively [96,97]. The model's predictive power surpasses that of random prediction, as shown by the AUC value of the training data in Figure A1. The results of the Jackknife test for the chosen variables in the model are presented in Figure A2.

SDM results display the areas with the highest potential for the species' present-day distribution (Figure 2). The greatest habitat suitability is shown on the map by a value of 1, and the least suitability is shown by a value of 0. More specifically, there is greater concentration around northern Türkiye along the Black Sea coast. As the species moves southwards from this region into inland areas, habitat suitability decreases.

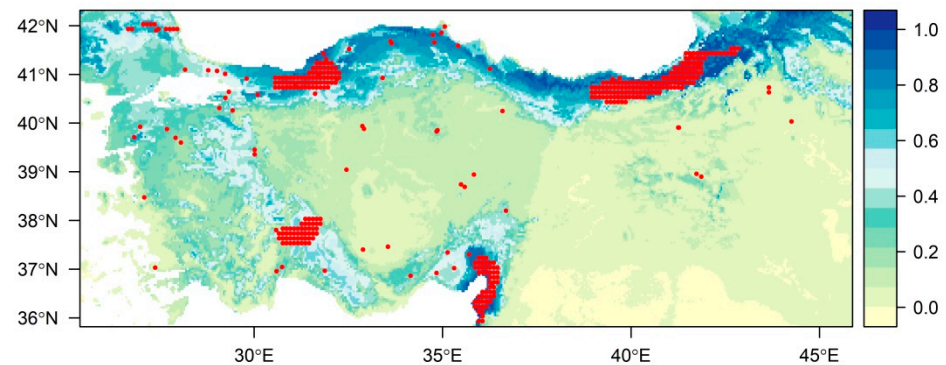


Figure 2. Present-day distribution of *Ulmus glabra* L. (red dots represent occurrence data).

U. glabra is currently expected to have a fragmented distribution in the western part of the Marmara Region, on the southern slopes of the Black Sea region, and along the Eastern Black Sea Mountain range; in the Eastern Anatolia Region; in the Mediterranean Region on the southern slopes of the Western and Central Taurus Mountains; in the Central Anatolia Region; and in the Aegean Region. The species is mainly found in the region that extends westward from the Georgian border along the eastern portion of the Black Sea coast. The red dots, representing the species' present range, are concentrated in this region and correspond to its natural range. Future projections for the species' distribution suggest potential positive (gain), neutral, and negative (loss) changes depending on different time periods and various scenarios (Figure 3).

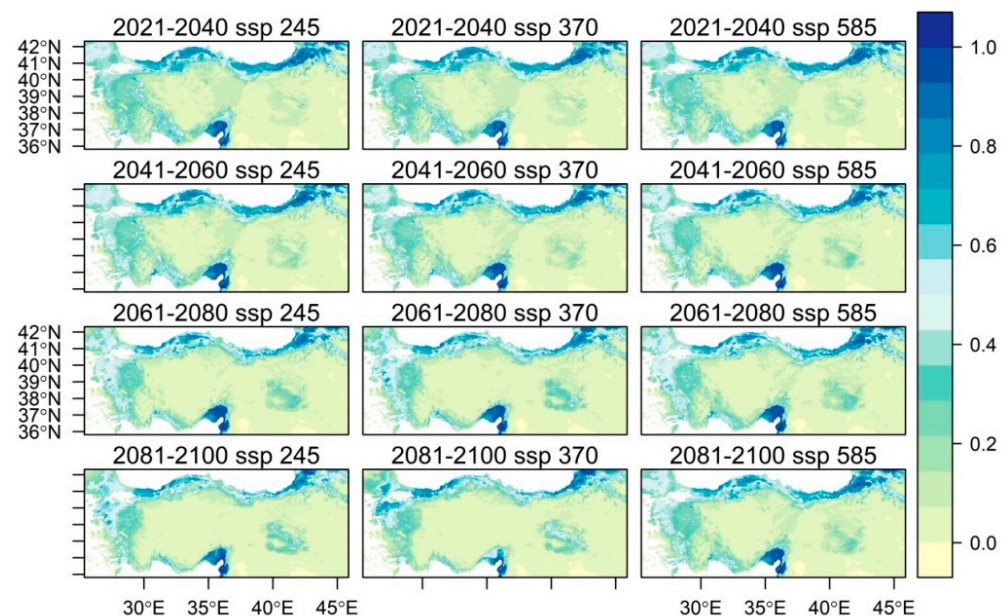


Figure 3. Projected average habitat suitability maps for *Ulmus glabra* L. under future climate scenarios. Average projections are presented for each of four periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100) and three shared socioeconomic pathways (optimistic: SSP245; middle of the road: SSP370; and pessimistic: SSP585). The probability of occurrence ranges from 0 (yellow, low probability) to 1 (dark blue, highest probability).

According to the SSP245 scenario, the potential range of the species is predicted to decline in the Erzurum-Kars and Ardahan Plateau, along the Eastern Black Sea mountain range, the Küre Mountains, the Ilgaz Mountains, the northern part of the Köroğlu Mountains, the Akçakoca Mountains, the eastern part of Marmara, Uludağ, and the eastern part of the Western Taurus Mountains. The species is anticipated to expand its distribution to encompass the northern Samanlı Mountains, the western Kaz Mountains, and the interior regions of the Aegean Region. The species will also continue to move along the eastern Marmara Region, the western Black Sea coast, and the coastal regions of the western Taurus Mountains between 2021 and 2040 and 2041 and 2060. It is anticipated that the distribution of the species in these regions will decline between the periods 2061–2080 and 2081–2100.

According to the SSP370 scenario, the distribution of the species is expected to decrease in the Erzurum-Kars and Ardahan Plateau, along the Eastern Black Sea mountain range, the Küre Mountains, the Ilgaz Mountains, the northern part of the Köroğlu Mountains, the Akçakoca Mountains, the mountainous interior regions of the Aegean Region, and the northwestern part of Çukurova. The species is predicted to be distributed in the eastern and southern coastal areas of the Marmara Region, the northern part of the Samanlı Mountains, Korudağ, the Işıklar Mountains, the northern Aegean coast, and the coastal areas of the Western Taurus Mountains. Between 2021–2040 and 2041–2060, the species is expected to increase its distribution in the coastal areas of the Western Taurus Mountains. However, between 2061–2080 and 2081–2100, the distribution of the species in these areas is anticipated to decrease. The species is expected to spread in the northern Aegean coastal areas and the southern part of the Kaz Mountains between 2061 and 2080. The range of the species will expand towards the Kayacı Mountains, northwestern Thrace, and the southern coasts of the Marmara Region between 2081 and 2100.

According to the SSP585 scenario, the distribution of the species is predicted to decline in the Ilgaz Mountains, the Köroğlu Mountains, Uludağ, and the interior regions of the Aegean Region. The species is expected to be distributed in the eastern part of the Marmara Region. Between 2021–2040, 2041–2060, and 2061–2080, the species is expected to expand in the mountain ranges along the coastal side of the Aegean Region and the coastal areas of the Western Taurus Mountains. However, between 2081 and 2100, the distribution of the species in these areas is expected to decline. The species is expected to maintain its distribution in the coastal areas of the Eastern Black Sea region and the Çukurova Region with almost no change under this scenario.

3.2. Predicted Outcomes in Habitat Suitability and Spatial Change for the Species

When examining the change in habitat suitability for *U. glabra*, the amount of suitable habitat areas under different SSP scenarios shows significant differences over time (Figure 4).

The species' habitat suitability is expected to decrease in the future according to different scenarios (Figure A3). When examining the spatial change in terms of gain and loss, it is predicted that there will be more loss than gain in all scenarios (Figure 5). The highest gains are expected, respectively, in the SSP585 scenario during the period 2081–2100, the SSP370 scenario during the period 2081–2100, and the SSP585 scenario during the period 2061–2080. The most significant losses are projected to occur in the SSP585 scenario during the 2061–2080 period, the SSP245 scenario during the period 2081–2100, and the SSP370 scenario during the period 2081–2100. In the SSP245 scenario during the period 2021–2040, the species' habitat suitability is expected to increase slightly (0.032%) while decreasing by 2.94%. Most of the loss is observed in the Black Sea Region. The species is shifting from the interior parts of the Black Sea to the coastal areas. The distribution areas exhibit significant spatial similarities in the SSP370 scenario during 2021–2040, except in the Marmara Region. In this scenario, the species expands westward in the Marmara. In the SSP245 scenario during the period 2041–2060, the species' habitat suitability is expected to increase slightly (0.047%) while decreasing by 5.03%.

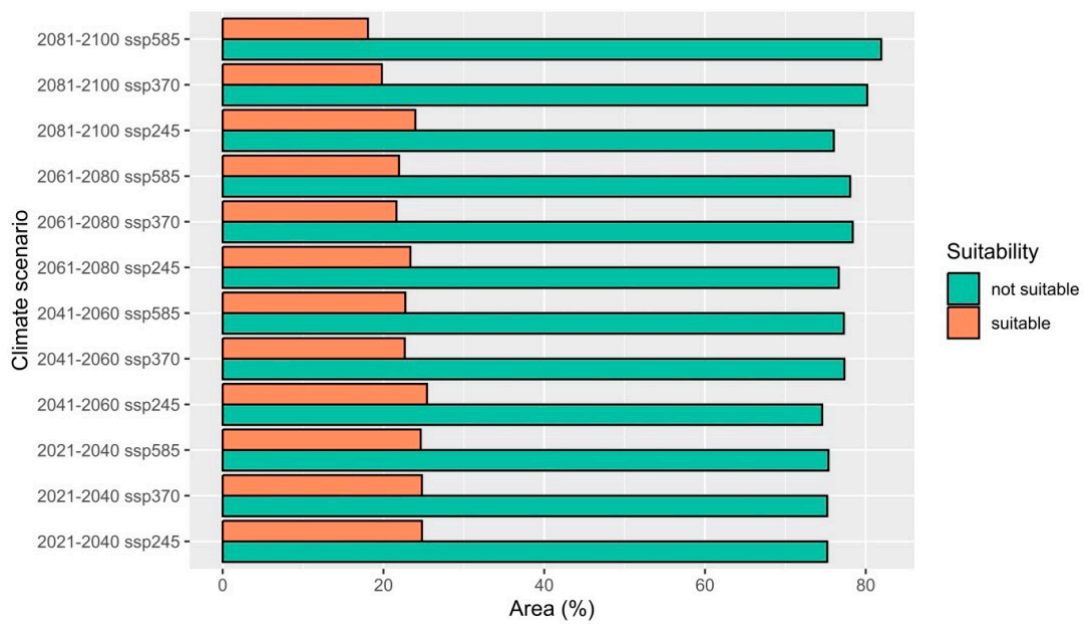


Figure 4. Change in total area suitable for the species according to different climate scenarios and time periods.

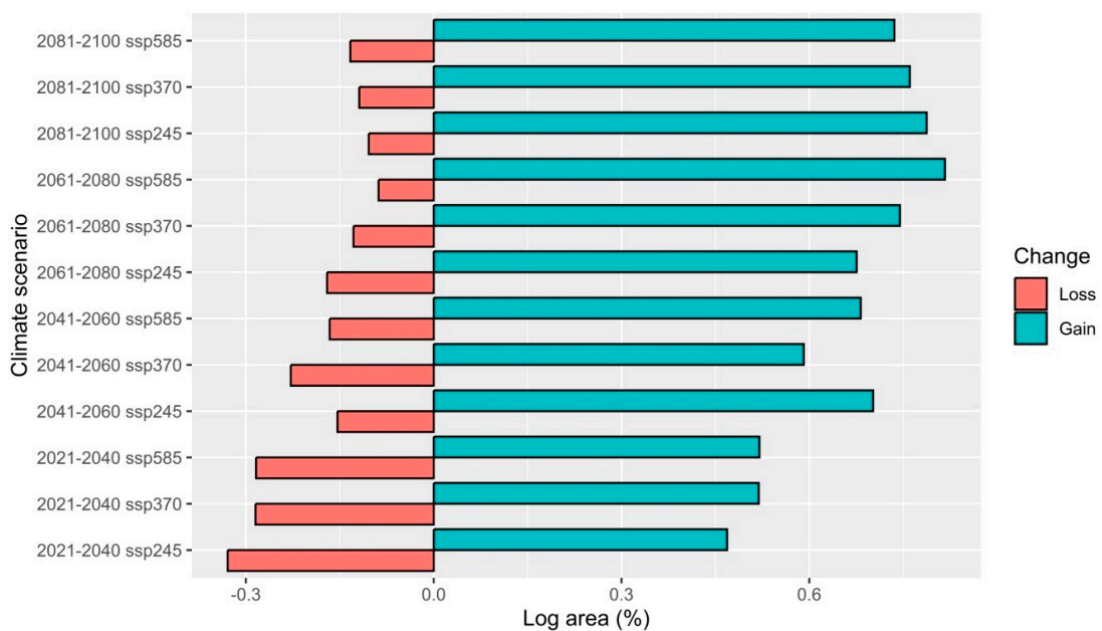


Figure 5. Gain and loss of distribution of the species under different climate scenarios.

In the SSP245 scenario during the period 2041–2060, the species’ habitat suitability is expected to slightly increase (0.047%) and decrease by 5.03%. The suitable area expands in the SSP370 and SSP585 scenarios. However, the area loss is 3.90% in the SSP370 scenario and 4.81% in the SSP585 scenario. Spatially, the majority of the loss is observed in the Black Sea Region and around the Western Taurus Mountains. The species is shifting towards the coastal areas in the Black Sea Region and southeast in the Western Taurus Mountains. Similarly, it is predicted to expand southward in Çukurova.

According to the SSP245 scenario for the period 2061–2080, the species’ habitat suitability is expected to slightly increase (0.065%) and decrease by 4.74%. Unlike other scenarios, this scenario expects the species to occupy the mountainous coastal areas of the Northern Aegean and the western coastal areas of the Eastern Black Sea. This distribution will

increase in the SSP370 scenario but will decrease in the SSP585 scenario. The suitability of the species is predicted to experience the most significant loss (6.56%) in the SSP585 scenario for the period 2061–2080.

According to the SSP245 scenario for the period 2081–2100, the species' habitat suitability is expected to slightly increase (0.072%) and decrease by 6.13%. In the SSP370 scenario, contrary to the general trend, the species' suitable habitat is expected to be located in Northern Aegean and Western Thrace. In the SSP585 scenario for the period 2081–2100, the suitable habitats will show a limited increase (0.125%). Although this increase is limited, it is greater than the gains in other scenarios and periods.

3.3. Morphological Spatial Pattern Analysis (MSPA) Results

Cores show spatial changes in the SSP245 scenario, with the exception of the Black Sea Region, the Marmara Region, the Mediterranean Region, and the northwest of the Aegean Region. The most significant rise in the amount of core area is recorded from 2081 to 2100 under this scenario. In particular, the core areas in the Aegean and Black Sea Regions demonstrate a significant expansion during this period, indicating a potential shift in habitat distribution for *U. glabra*. Bridges, although showing similar spatial distributions throughout each period, are most extensively spread in the southwestern inner part of the Aegean Region from 2061 to 2080, contributing to an increase in habitat connectivity in these areas. Small core areas are more likely to have bridges and branches around them compared to large core areas. Islets, which represent small isolated habitats, are more prominent in the Southeastern Anatolia Region, showing ongoing fragmentation and a loss of connectivity in these areas (Figure A4).

For the SSP370 scenario, cores show significant changes in the Black Sea and Mediterranean regions from 2021 to 2060. The most notable shift occurs in the Marmara Region, where core areas expand, and new connections form through bridges during this period. Bridges are concentrated in the Aegean and Mediterranean Regions during 2021–2040 and 2041–2060. However, there is a notable reduction in connectivity from 2061 to 2100, leading to increased habitat isolation. Branches and islets are mostly found around the edges of the Aegean, the Mediterranean, Central Western Anatolia, and the interior parts of the Black Sea Region. Unlike other periods, in 2081–2100, cores, loops, bridges, branches, and islets are concentrated in the Southeastern Anatolia Region.

Under the SSP585 scenario, the core area is dramatically reduced during 2081–2100, especially in the Black Sea and Mediterranean regions. The spatial distribution of bridges and loops decreases significantly during this period, indicating a loss of ecological corridors critical for species movement. Bridges are most concentrated in the Mediterranean and Aegean Regions from 2021 to 2040. Therefore, these facts suggest that habitat fragmentation will be most severe under this scenario by the end of the century.

The most significant increase in core area is observed in 2021–2040 under the SSP585 scenario and 2061–2080 under the same SSP585 scenario. The dramatic decrease in core area occurs in 2081–2100 under the SSP585 scenario and 2041–2060 under the SSP245 scenario (Figure 6A).

The graph shows fluctuations in the amount of core area over time, with sharp declines in some scenarios. Notably, the core area percentage significantly decreases in 2081–2100 under the SSP585 scenario. While an upward trend is observed under the SSP585 scenario, other scenarios exhibit more variable trends. However, a decline is observed in all scenarios by 2100.

In Figure 6B, the bridges show different patterns across three scenarios and periods. For instance, in the SSP245 scenario, bridges decrease during 2021–2040 but increase during 2041–2060 and 2081–2100. Conversely, the SSP370 scenario shows a bridge increase from 2021 to 2040, followed by a decrease between 2041–2060 and 2081–2100. On the other hand, the SSP585 scenario indicates the highest bridge increase during 2021–2040, followed by the most significant decline from 2041 to 2060, extending the period 2081–2100. The Sankey diagrams (Figure 7) illustrate the morphological transformations of MSPA units

under SSP245, SSP370, and SSP585 scenarios across four different time periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100).

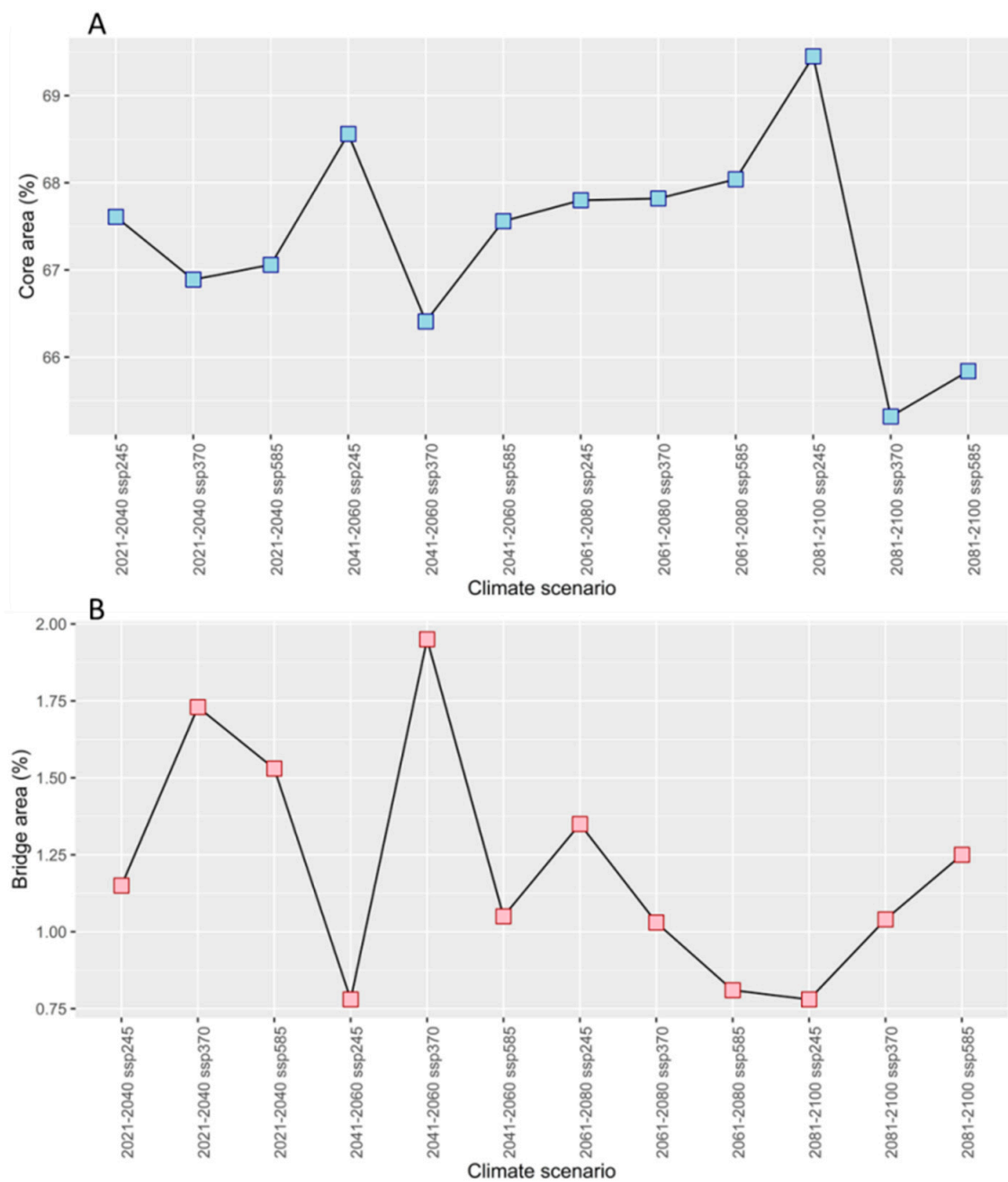


Figure 6. Changes in core area and bridge area under different climate scenarios. **(A)** Core area percentage across various climate scenarios (SSP245, SSP370, SSP585) for the periods 2021–2040, 2041–2060, 2061–2080, and 2081–2100. The core area shows fluctuations with a notable increase in the period 2081–2100 under SSP245. **(B)** Bridge area percentage across the same climate scenarios and periods. The bridge area also shows variability, with peaks observed in the periods 2041–2060 under SSP245 and 2081–2100 under SSP585.

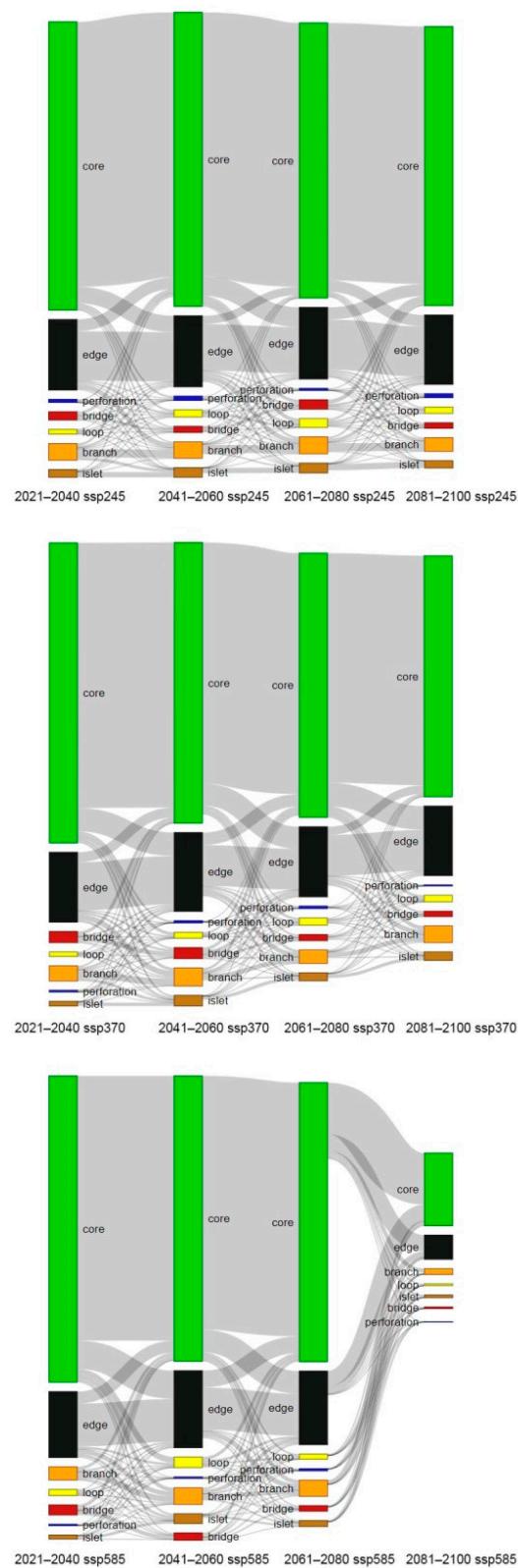


Figure 7. Changes in landscape structure under different SSP scenarios from 2021 to 2100. This figure illustrates the transitions between different landscape structures (core, edge, perforation, bridge, loop, branch, and islet) across four time periods (2021–2040, 2041–2060, 2061–2080, and 2081–2100) under three shared socioeconomic pathway (SSP) scenarios (SSP245, SSP370, and SSP585). Each section represents the distribution and transformation of MSPA units over time.

During the SSP245 scenario, there is a shift from core areas into edge and perforation areas where fragmentation occurs from 2021 to 2040. This transformation process continues up to 2041–2060, with a notable reduction in nodes and bridges and a decrease in isolated habitat units such as islets and branches. As time progresses, the increase in edge and perforation areas demonstrates the ongoing reduction in core habitats. In the 2021–2040 period of the SSP370 scenario, fragmentation and disconnection occur rapidly and extensively. The core areas experience a shift towards the edge and perforation areas. Branches and islets become more pronounced. From 2041 to 2060, core areas decrease dramatically along with ecological connectors such as bridges or loops which lead to increased isolation. In the later periods, there was an expansion in the edge and perforation patterns, indicating that these areas have been heavily affected by challenging climate change conditions under this scenario. Under the SSP585 scenario, a faster transition from core areas to edge and perforation areas continues up to the period 2041–2060. An increase in units like branches or islets shows that the landscape becomes more fragmented and disconnected. From 2061 to 2080, there is a significant reduction in core areas, with edge and perforation areas becoming more prominent. By 2081–2100, the SSP585 scenario profoundly alters the fundamental structure of the landscape, with cores nearly disappearing, leading to a substantial decline in the connectivity of the landscape. These transformations indicate the continuous decline in habitat integrity and ecological connections.

3.4. The Connectivity Importance (*dPC*)

The maps showing connectivity importance (*dPC*) reveal that different scenarios have varied levels of significance for patches acting as stepping stones within the study area over time (Figure A5). The most notable changes occur during 2081–2100 under the SSP245 scenario, where the eastern Marmara Region becomes highly important, followed closely by western parts of the Black Sea Region. This indicates the shifting importance of key habitat nodes that support species movement, highlighting the need for conservation efforts to focus on these areas as crucial connectivity corridors. In addition, node regions shift across periods, peaking at maximum number during 2041–2060, but some locations, such as the central inland region, the Black Sea coast, and the Mediterranean, remain constant throughout all periods, suggesting persistent ecological connectivity despite external pressures.

In SSP370 highest importance is shown in the 2021–2040 period along the northern coast of the Sea of Marmara. Ecological networks remain highly concentrated, but fragmentation risks increase over time. Although the number of loops changes between periods, the highest number is expected in 2041–2060. The locations of connectivity landscape patches vary but remain approximately close to each other, with increased fragmentation observed towards the later periods, indicating the loss of long-term connectivity. In 2081–2100, new nodes and connectivity-providing landscape patches form in the Southeastern Anatolia Region. The northern inland part of the Marmara Region, which had low importance in the period 2021–2040, rises to moderate importance in 2041–2060.

In the SSP585 scenario, the highest importance is observed in the 2061–2080 period, focusing on the northwestern part of the Aegean Region. The connectivity in these regions will play a significant role in supporting fragmented populations in the face of increasing habitat pressures. The area of node habitats changes between periods, with the most node landscape patches observed in the 2041–2060. The northern coastal area of the Sea of Marmara, which had high importance in the period 2021–2040, loses its importance in subsequent periods. This loss of connectivity will likely isolate key populations, raising concerns for species conservation. Connectivity units change over time, with the highest connectivity observed in the 2021–2040 period. The high-importance connectivity patch in the southwestern inland part of the Aegean Region in scenario 2061–2080 disappears in 2081–2100. This disappearance points to increased fragmentation and loss of habitat, potentially leading to local extinctions. In 2061–2080, connectivity increases in the Southeastern Anatolia Region compared to the 2021–2040 and 2041–2060 periods. Similarly, connectivity

increases in the middle and eastern inland parts of the Black Sea Region and the Eastern Anatolia Region in 2081–2100. High-importance connectivity and node patches form in the inland part of the Black Sea Region in 2081–2100.

4. Discussion

Increases in temperature, changes in precipitation patterns, and more frequent extreme weather events pose threats to many plant species [98]. These outcomes lead to significant changes in elms' distribution, morphology, and genetic diversity, as seen in other plant species [61]. Developing measures for adaptation to global climate change in Türkiye will need the protection and sustainable management of the morphological characteristics of the elm species [61]. The results of this study showed that, depending on the climatic scenarios, the habitat suitability of *Ulmus glabra* varied significantly. The species is expected to face habitat fragmentation and loss, and therefore, conservation and management strategies need to be developed.

Climate change can trigger ecological processes such as habitat loss and fragmentation, leading to adverse effects on biodiversity [35]. *U. glabra* prefers riverbanks, higher humidity levels, higher altitudes, and nutrient-rich soils than any other elm species; hence, it is prone to changes in moisture content and drought stress [99]. Fragmentation of habitat alters vegetation density, soil structure, and organism populations, either through human activities or natural events. Climate change affects riparian landscapes, which are characterized by interaction between land and water bodies [100]. Species like *U. glabra*, which are sensitive to climate alterations, will be most affected.

U. glabra plays an important role in forest ecosystems through complex ecological relationships formed by association with other species. The impacts of climate change on the species can cause ripple effects in relation to other species that are ecologically linked with it. For instance, changes at microhabitat levels may directly affect understory vegetation and forest floor species developing under elm stands. Moreover, many bird, mammal, and insect species use these stands as their shelters or food sources. Insects and bees feed on flowers that bloom before leaves, while red squirrels and other rodents feed on seeds dropped by this tree species. A reduction in habitat suitability for *U. glabra* could have negative impacts on populations and ecological networks of such animal species, thereby resulting in habitat loss coupled with inter-species interaction breakdowns within affected communities or regions. This suggests that any measures taken towards adapting against climate change should not only target an ugly bark but also consider its wider implications in relation to other components of the ecosystems. Thus, it reflects the need for preserving intra-specific dynamics within the broader context of conserving biodiversity. This discussion, therefore, implies enhancing resilient forest ecosystems against potential climate change impacts through integrated management approaches.

The Shuttle Radar Topography Mission (SRTM) dataset contributes to the creation of bioclimatic data by factoring in elevation, which inherently captures terrain variation. During the creation of WorldClim2 data, Fick and Hijmans [73] reported that elevation data were aggregated from the SRTM with a 30 arc-second spatial resolution, covering regions between 60° N and 60° S. These elevation data were then used as one of the covariates in climate surface interpolation. Since terrain variation is influenced by changes in elevation, the inclusion of SRTM data ensures that terrain features, such as mountainous regions or steep gradients, are considered in climate models. However, the limitation of this approach is that it may not fully capture localized topographical nuances, particularly at finer spatial scales. The 30 arc-second resolution, while suitable for broader elevation trends, might not sufficiently reflect the micro-scale terrain variations that are critical in regions like the northern border of the plateau, where steep gradients and localized features significantly influence species distribution and connectivity. This is one limitation of the study.

One of the foundational concepts in ecology is the distinction between the fundamental and realized niches [101]. The fundamental niche represents the potential distribution of a species in the absence of biotic interactions, while the realized niche reflects the actual

distribution shaped by these interactions. This framework is essential for understanding how species coexist and how their distributions may shift in response to environmental changes [57,58]. For instance, Araújo et al. [102] highlight that species can inhabit areas outside their abiotic niches due to biotic interactions, such as competition or resource availability, which can significantly influence their distribution patterns. Another limitation of this study is the lack of consideration for biotic factors.

Despite multicollinearity issues, modeling studies identified six key bioclimatic variables that are significant for determining habitat suitability. These variables emerged as factors significantly affecting the species' distribution and habitat preferences. Model results showed that the species' habitat suitability is particularly sensitive to factors such as annual precipitation, seasonal temperature variation, and isothermality.

Habitat changes in elm stands can significantly alter the distribution of resources such as light, humidity, and nutrients within the ecosystem. These changes can affect the composition and diversity of plant communities in the understory and forest floor. Changes in the light regime can especially benefit light-sensitive species, causing them to become dominant. Similarly, changes in soil moisture and nutrient distribution can redefine niches within the ecosystem based on different species' adaptation capabilities to these new conditions. There can be mismatched pairings between wind-pollinated and self-pollinated elms [66]. This process can contribute to reshaping species diversity and structural complexity within the ecosystem. Previously suppressed or scarce species may find opportunities to grow and spread with the decline of elms. So, this may lead to significant modifications in the dynamics of the species in an ecosystem and new forms of environmental balance.

To address future research and conservation strategies for *U. glabra*, we suggest incorporating a broader approach that evaluates not only the species in isolation but also its interactions with associated species within the same habitat. As the study highlights the intricate ecological relationships between *U. glabra* and other species, it would be beneficial to examine how these associations influence the overall ecological connectivity and species survival under climate change scenarios. Future assessments should emphasize investigating *U. glabra* in conjunction with other plant species commonly found in its stands, such as *Fagus sylvatica* (beech), *Quercus robur* (oak), *Acer pseudoplatanus* (sycamore), *Fraxinus* spp. (ash), and others that share its habitat and environmental needs.

Understanding the shifting movement of the species in the ecosystem entails reframing its interactions with the other species. Ecosystem management and biodiversity conservation should take into account this movement and potential new links (connections). Increasing the adaptability of ecosystems, making them more resilient to potential climate change impacts, should be an essential objective of sustainable ecosystem management. Therefore, identifying the new ecological connections that may form between *U. glabra* and associated species is relevant for the future health and stability of ecosystems.

The results of connectivity analysis with MSPA showed that there would be a persistent degradation in the ecological connectivity of the species. The number of cores varies by geographical location and time, with substantial decreases reported in examined periods. The decline in core areas, along with an increase in edge and perforation amounts, causes isolations among morphological units, resulting in habitat fragmentation. This indicates the need for conservation of the species in future forest planning and management.

The importance of connectivity (*dPC*) analysis showed how ecological connections and habitat fragmentation might change over time and under different climate models. The levels of connectivity of landscape patches varied across all scenarios and periods. Significant connection and node patches were identified in the interior regions of the Black Sea and the northwest of the Aegean Region. The patch locations providing connectivity are unique for each scenario at each time step. Thus, it is necessary to consider temporal changes occurring in landscape structure when developing habitat conservation or management strategies.

The ecological connectivity of *U. glabra* may change over time due to the expansion or contraction of the morphological spatial pattern units in Türkiye. Consequently, this study provides important insights into the potential future habitat suitability of *U. glabra* and the transformations of the spatial pattern units. The findings indicate the need to design robust strategies for conserving the species against the adverse effects of climate change.

5. Conclusions

This study demonstrates that *U. glabra* is highly vulnerable to climate change, with habitat fragmentation and a significant decline in ecological connectivity expected in the coming decades. By utilizing species distribution modeling (SDM) and Morphological Spatial Pattern Analysis (MSPA), the study supports that habitat suitability for the species is likely to decline across all climate scenarios, particularly under SSP585, where the species may lose substantial portions of its habitat by 2100. The core areas that provide essential ecological connections will shrink, and fragmentation indicators such as edges and perforations will increase, leading to greater isolation of habitats. These findings highlight the importance of enhancing conservation efforts and developing adaptive management strategies to preserve *U. glabra* and its ecosystem functions within Türkiye.

One of the novel aspects of this research lies in integrating the species' future habitat projections with connectivity analysis, providing a robust framework for landscape-scale conservation planning. The results underline the need for targeted conservation actions, particularly in regions like the Black Sea and Aegean, where critical connectivity nodes and core habitats are likely to undergo significant changes. In addition, by identifying potential areas of gain and loss, this study offers practical insights for prioritizing conservation areas and mitigating the impacts of climate change on the species.

Future research should build on this study by exploring the species' interactions with co-existing flora and fauna to better understand the broader ecological implications of habitat changes. Implementing effective conservation strategies that consider current and future landscape structures will be vital to conserving the species and ensuring the resilience of Türkiye's forest ecosystems.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Bioclimatic variables and their descriptions (WorldClim v2.1 database [73]).

Code	Description
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)

Table A1. Cont.

Code	Description
BIO5	Max Temperature of Warmest Month
BIO6	Min Temperature of Coldest Month
BIO7	Temperature Annual Range (BIO5–BIO6)
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

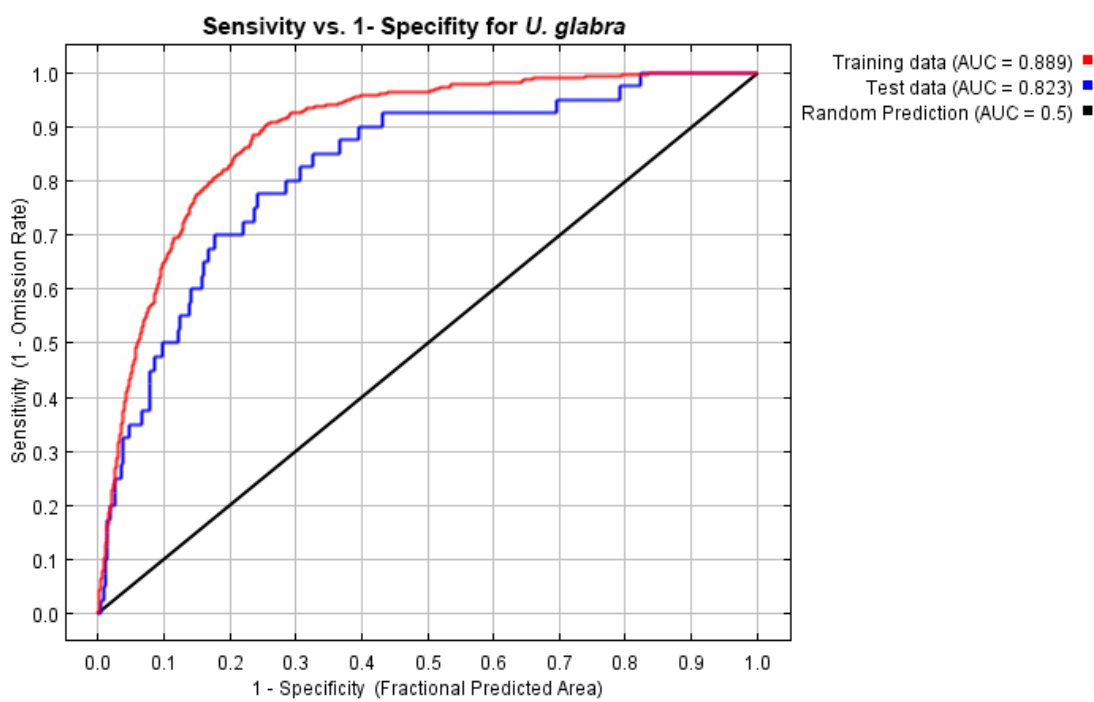


Figure A1. ROC curve.

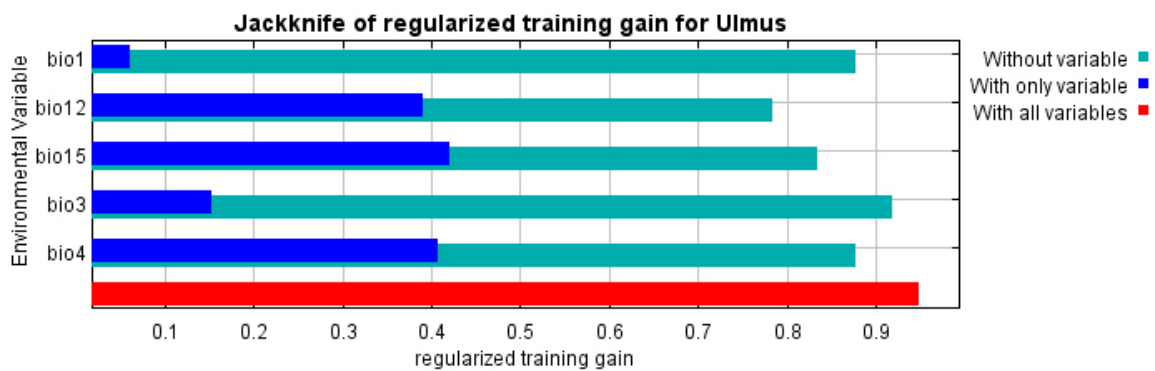


Figure A2. Jackknife test results of the selected variables in the model.

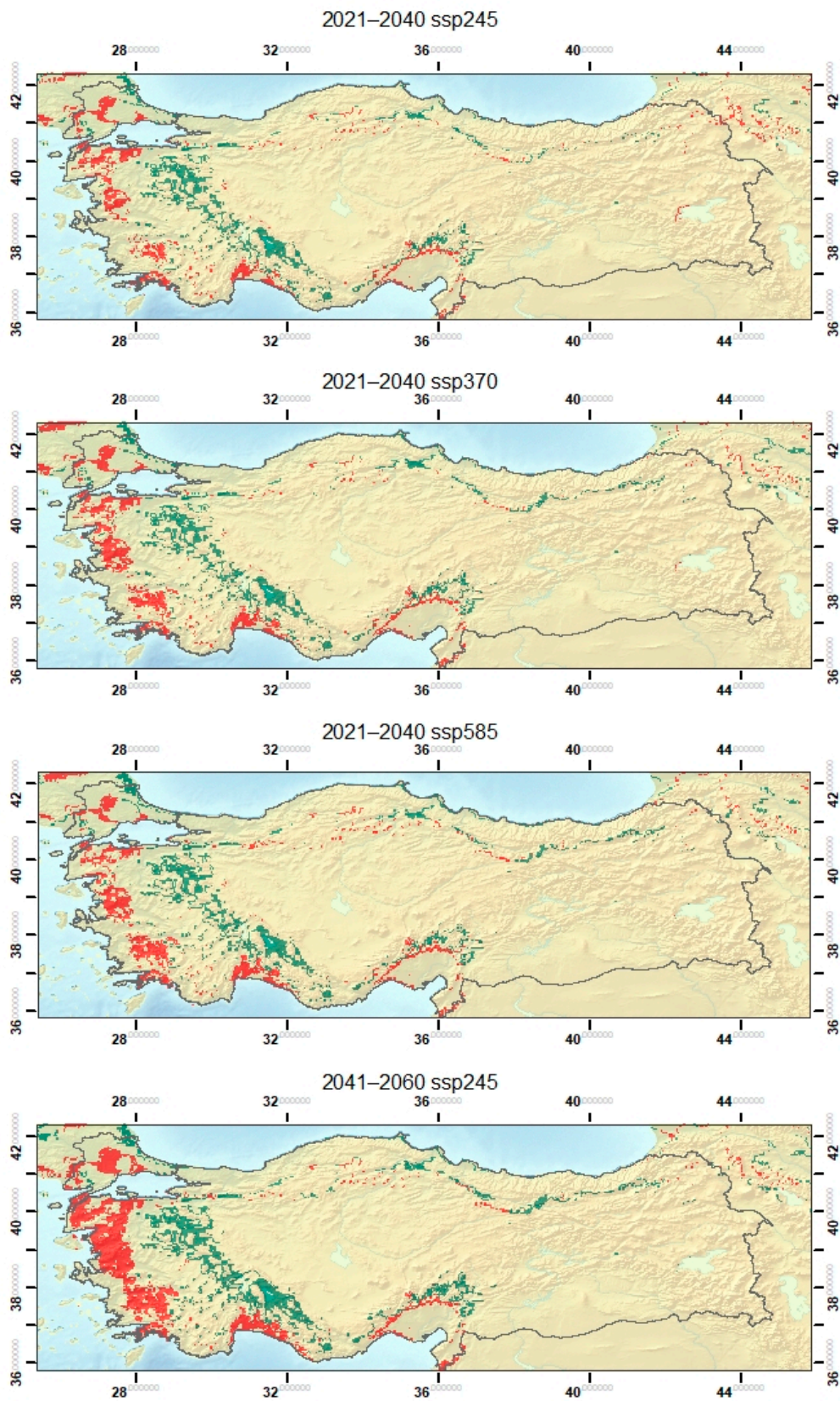


Figure A3. Cont.

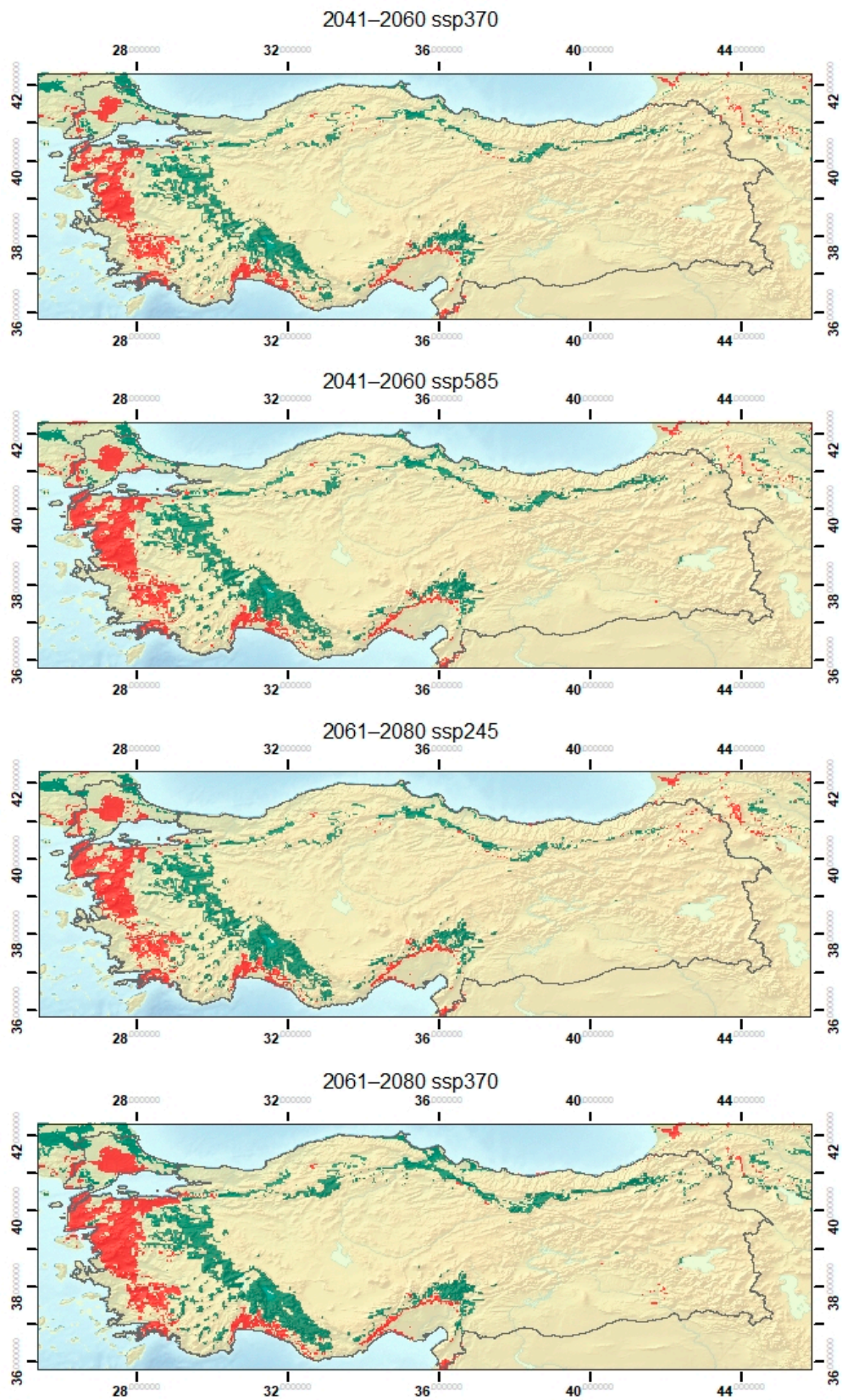


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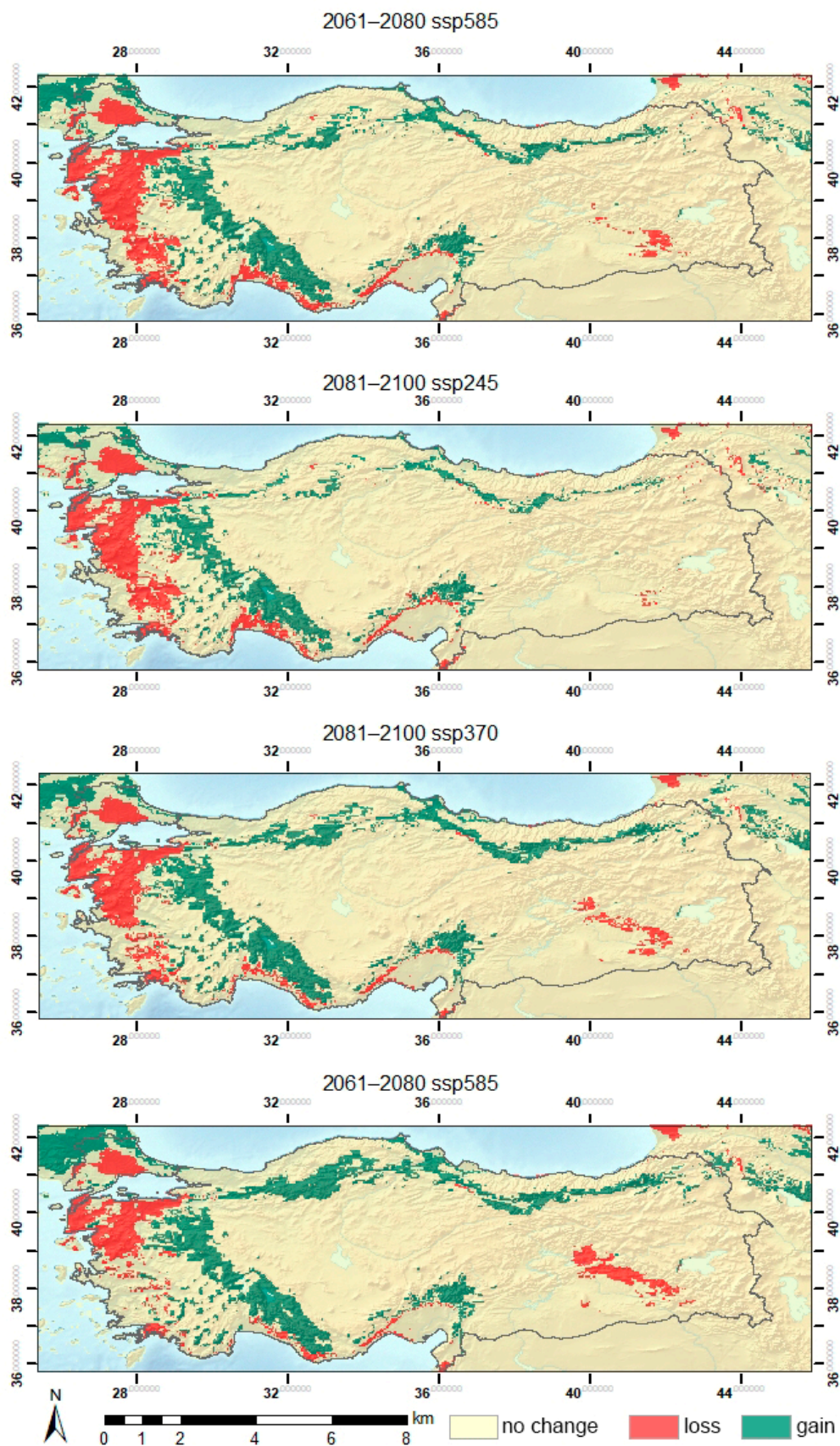


Figure A3. The spatial changes in habitat suitability of *U. glabra* under different SSP scenarios from 2021 to 2100.

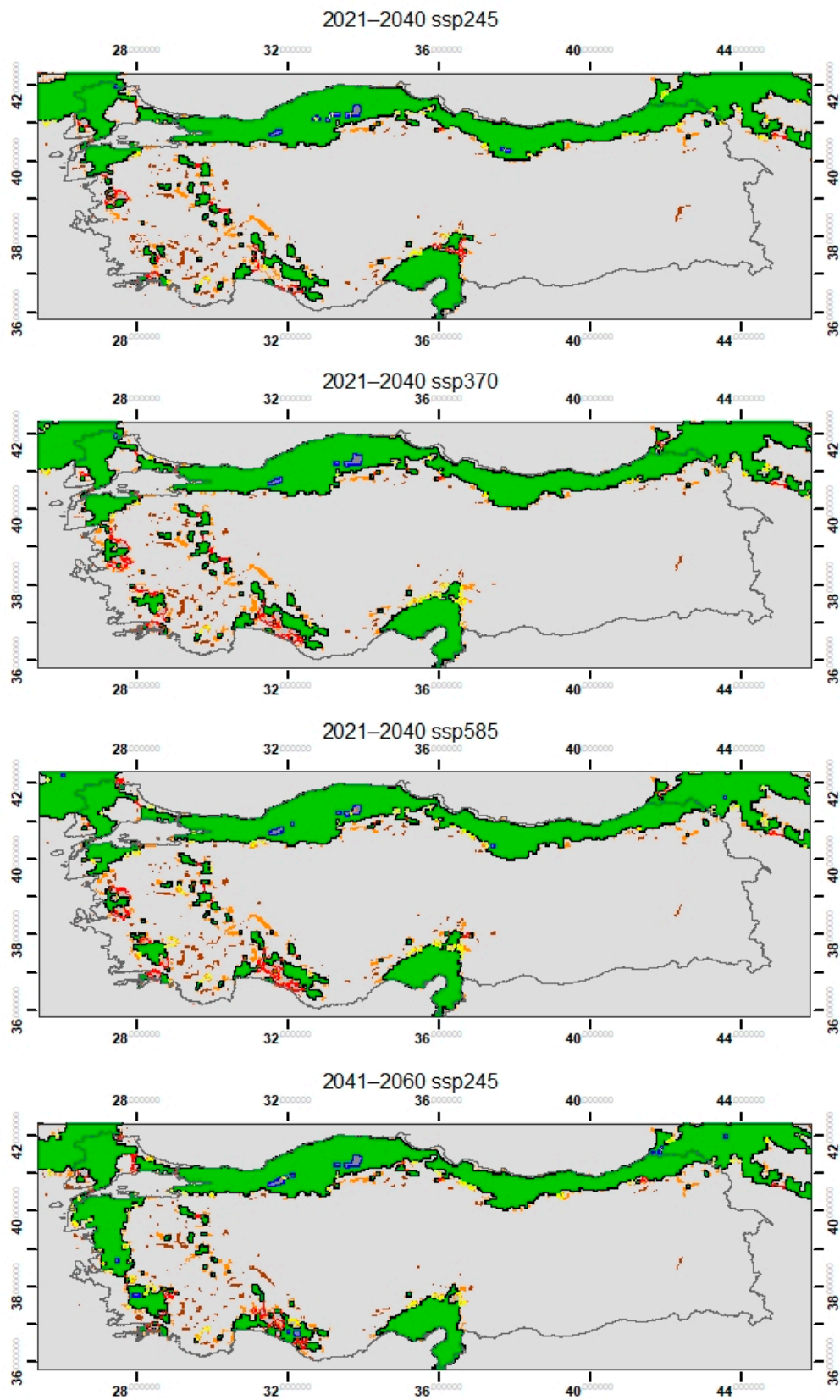


Figure A4. Cont.

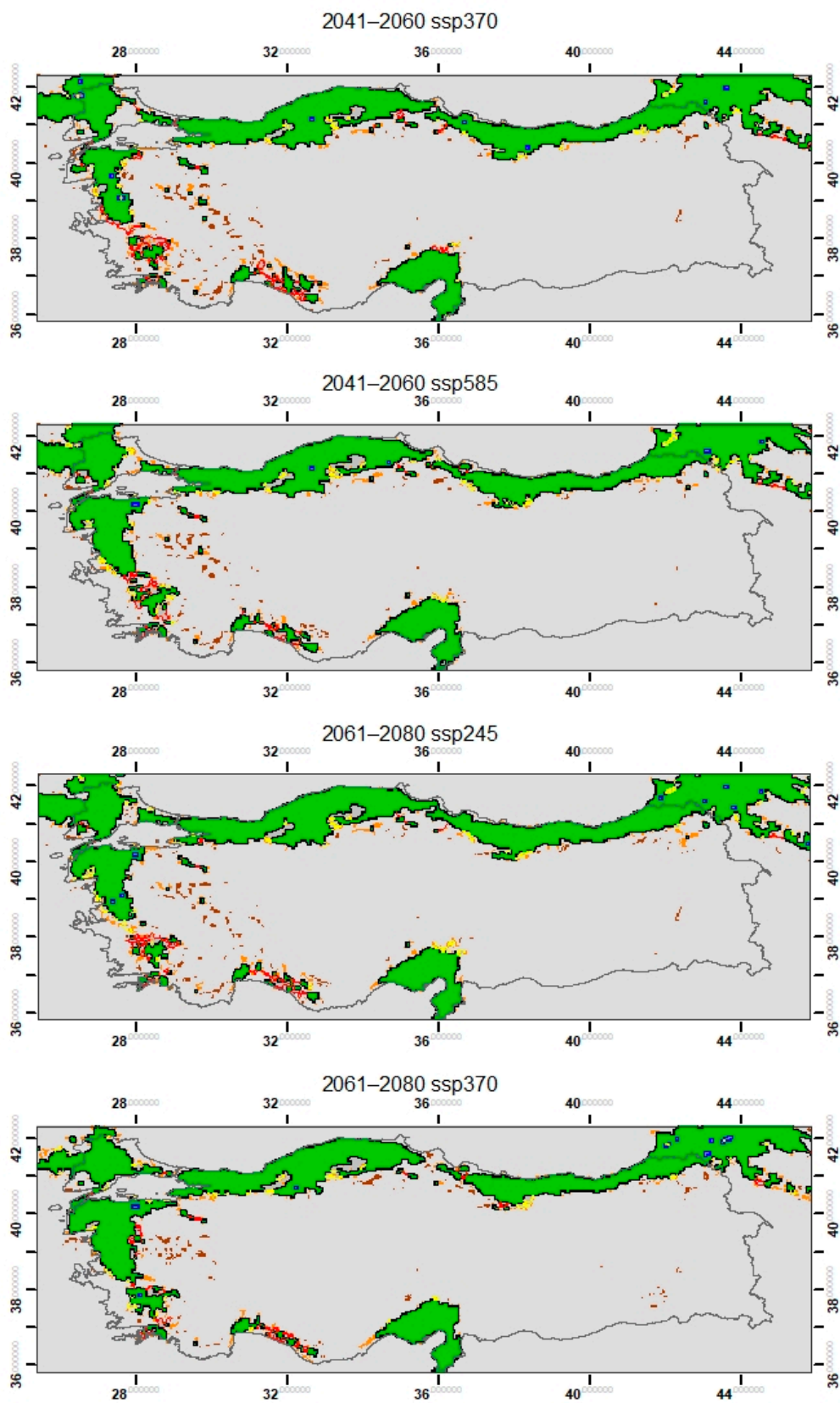


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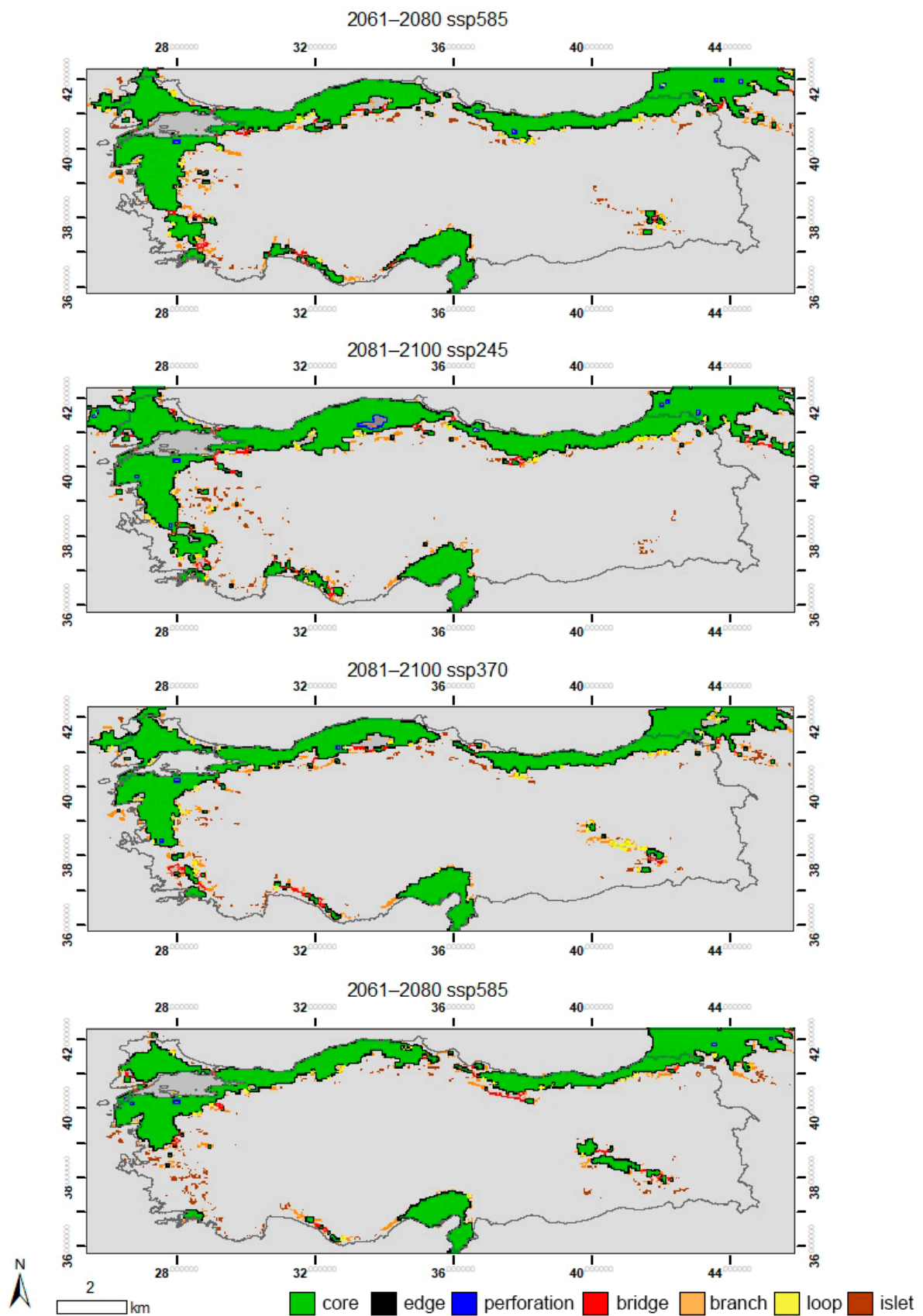


Figure A4. Change in morphological spatial pattern units under different SSP scenarios from 2021 to 2100.

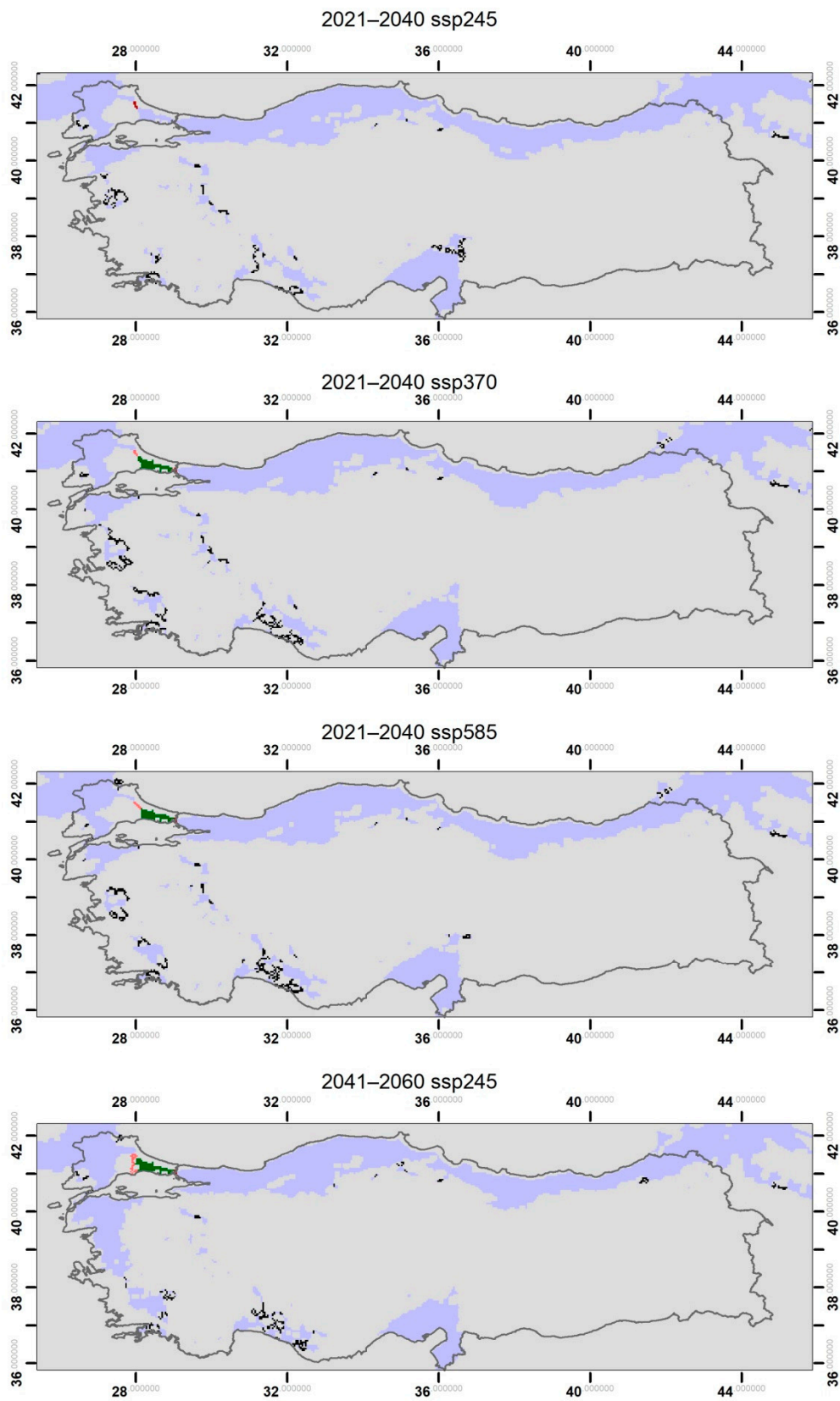


Figure A5. Cont.

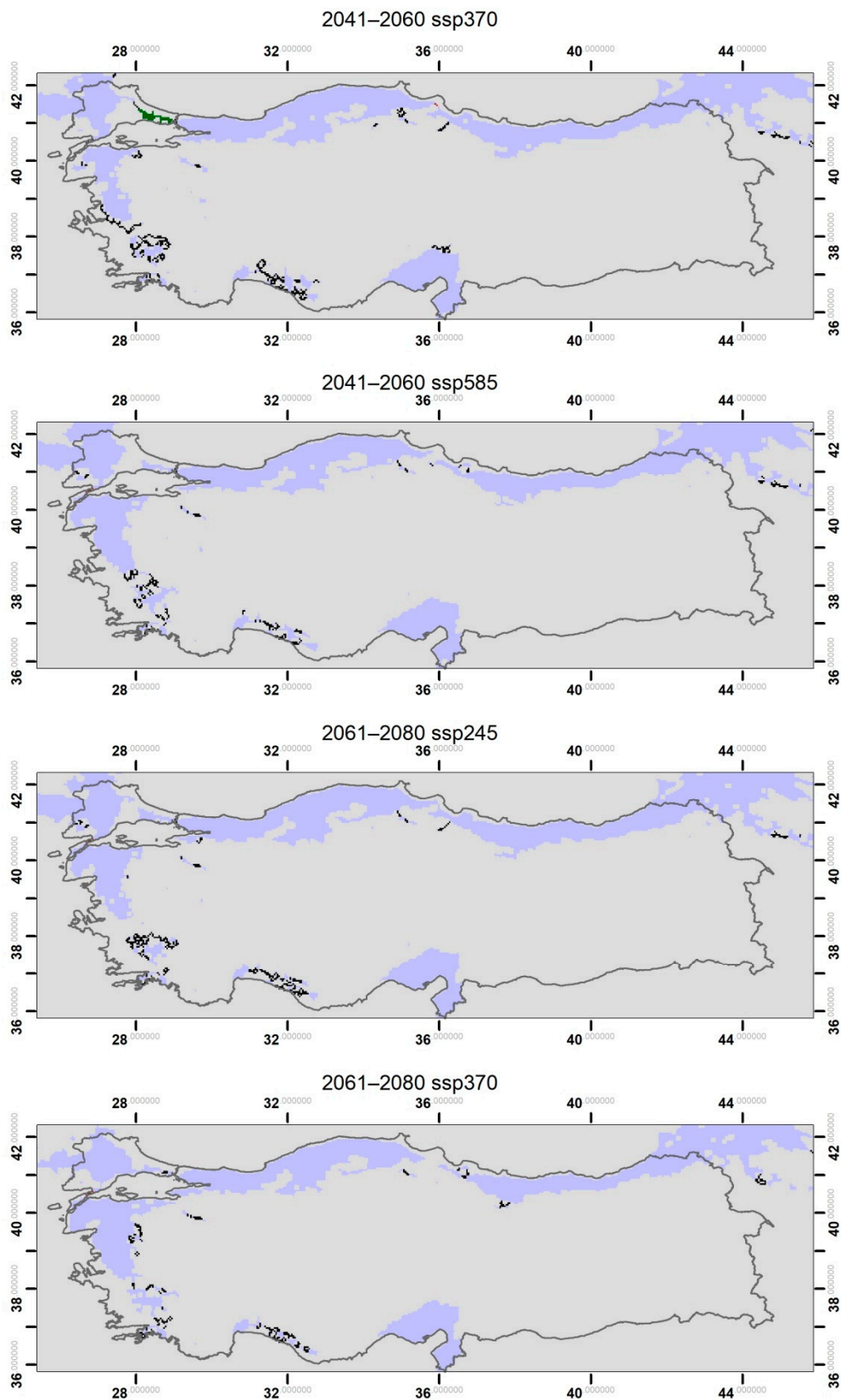


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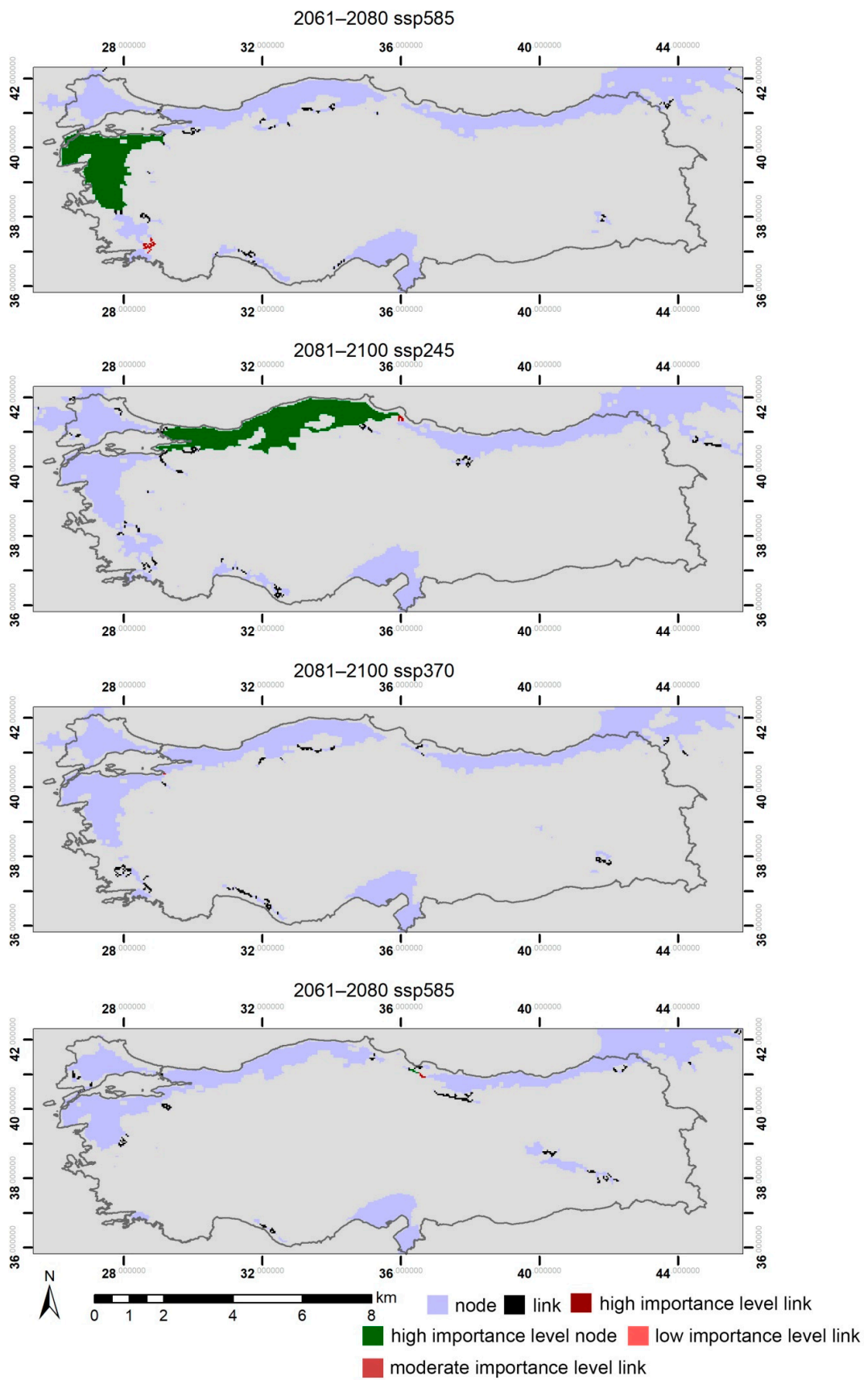


Figure A5. Change in the importance of connectivity (dPC) under different SSP scenarios from 2021 to 2100.

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