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Assessing climate change impacts on the spatial distribution of *Castanea sativa* Mill. using ecological niche modeling

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ABSTRACT **Research Article**

In recent decades, ecological niche modeling (ENM) has become integral for assessing climate change impacts on species distributions. In this study we conducted a comprehensive ENM using the Kuenm R package, employing MaxEnt as the modeling algorithm, to evaluate the impact of climate change on the habitat of *Castanea sativa* Mill., a non-wood forest species of high commercial interest in Turkiye, within the limits of the Trabzon Regional Directorate of Forestry (RDF). Predictors related to the species' ecology were carefully selected. The Future distributions of *C. sativa* for 2061–2080 under Shared Socio-economic Pathways (SSPs) 1-2.6, 2-4.5, and 5-8.5 were modeled using predictions from the Hadley Centre Global Earth Model HadGEM-GC31-LL. Extensive calibration modeling with Kuenm resulted in 434 models, and the most robust model, determined by statistical significance, predictive power, and complexity, revealed a drastic reduction in suitable areas for *C. sativa* (ranging from 86% to 99% across SSPs). The critical values of bio1 and bio5 were identified as primary factors. Predictions suggest potential migration of *C. sativa* to higher latitudes or elevations seeking more favorable climatic conditions. The substantial reduction in habitat suitability, even under SSP1-2.6, poses a significant threat, emphasizing the need for urgent measures to mitigate climate change impacts and ensure the species' survival and continuity.

Key Words: Non-wood forest products, climate change, environmental conditions, bioclimatic variables, Kuenm

İklim değişiminin *Castanea sativa* Mill.'in konumsal dağılımı üzerindeki etkilerinin ekolojik niş modelleme kullanılarak değerlendirilmesi

ÖZ

Son yıllarda, ekolojik niş modelleme (ENM), iklim değişikliğinin tür dağılımları üzerindeki etkilerini değerlendirmenin ayrılmaz bir parçası haline gelmiştir. Bu çalışmada, Trabzon Orman Bölge Müdürlüğü (OBM) sınırları içerisinde, Türkiye'de ticari açıdan değerli bir odun dışı orman ürünü olan *Castanea sativa* Mill.'in iklim değişikliğinin habitatı üzerindeki etkisini değerlendirmek için Kuenm R paketini kullanarak ve modelleme algoritması olarak MaxEnt'i kullanan kapsamlı bir ENM gerçekleştirdik. Türün ekolojisine ilişkin tahmin ediciler dikkatle seçilmiştir. *C. sativa*'nın gelecekteki dağılımı (2061-2080), Hadley Centre Global Earth Model HadGEM-GC31-LL kullanılarak SSP 1-2.6, 2-4.5 ve 5-8.5 altında modellenmiştir. Kuenm ile yapılan kapsamlı kalibrasyon modellemesinde 434 model ortaya çıkmıştır. İstatistiksel anlamlılık, tahmin gücü ve karmaşıklığa göre belirlenen en uygun model, *C. sativa* için uygun alanlarda (SSP'ler arasında %86 ile %99 arasında değişen) ciddi bir azalma olduğunu ortaya çıkarmıştır. Bu azalma öncelikle bio1 ve bio5 değişkenlerinden kaynaklanmaktadır. Bu tahminler, *C. sativa*'nın daha uygun iklim koşullarını aramak için daha yüksek enlemlere veya yüksekliklere göç etme potansiyelini göstermektedir. SSP1-2.6 altında bile habitat uygunluğunun azalması, tür için ciddi bir tehdit oluşturmakta olup, iklim değişikliğinin etkilerini hafifletmek ve türün hayatta kalışını ve sürekliliğini sağlamak için acil önlemlerin alınmasını gerektirmektedir.

Anahtar Kelimeler: Odun dışı orman ürünleri, iklim değişikliği, çevre koşulları, biyoklimatik değişkenler, Kuenm

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1. Introduction

Castanea sativa Mill., commonly referred to as "Sweet Chestnut", is a deciduous tree belonging to the Fagaceae family widely distributed from the East Black Sea to the Marmara and Aegean regions in Türkiye (Ketenoglu et al., 2009). Its presence holds great significance, as it plays a multifaceted role in the country's cultural, economic, and ecological landscape. Not only does *C. sativa* serve as a valuable food resource, but it also makes vital contributions to biodiversity and sustainable agriculture within the region. Furthermore, as a non-wood forest product (NWPF), it assumes a pivotal role in the foreign trade of Türkiye forest products, with exports being especially noteworthy. Official reports indicate the existence of 74,897 hectares of *C. sativa* forests, contributing significantly to the national economy with a recorded value of 176 million dollars in 2019, as well as exports worth 35 million dollars (CFE, 2020).

The sustainable management of national forests hinges on a comprehensive understanding of how climate change influences species distribution. Central to this understanding is the fundamental assumption of biogeography, which underscores the preeminent role of climate in determining the natural distribution of organisms (Wiens et al., 2009). Extensive research highlights the profound impact of climate change on both the expansion and contraction of species' ranges (e.g., Elith et al., 2010; Franklin et al., 2016; Pearson and Dawson, 2003; Thuiller et al., 2005). Given the undeniable consequences of past global warming, including biodiversity loss, ecosystem degradation, and alterations, the looming risks associated with further global warming are imminent and substantial (IPCC, 2023).

To address the complexities of understanding the potential effects of future climate change on species and their ecosystems, ecological niche models (ENMs) have risen to prominence (Guisan and Zimmermann, 2000; Morin and Lechowicz, 2008). These models, founded on niche theory, have proven indispensable in forecasting the potential impacts of climate change on biodiversity, particularly by focusing on the fundamental niche or the abiotically suitable range. Among the numerous ENM techniques, the correlative approach, often called habitat models, establishes statistical relationships between environmental variables and observed species occurrences (Franklin, 2010). The underlying assumption when employing these models to project future distributions is that the encapsulated variables faithfully represent the requirements of the species for a specific niche (Wiens et al., 2009).

One of the prominent correlative models employed within ENM is MaxEnt (maximum entropy). This modeling approach predicts the fundamental niche based on environmental data, effectively finding the probability distribution that is maximally uniform (maximum entropy) while aligning with known species occurrences relative to available environmental conditions (Phillips et al., 2006; Phillips and Dudík, 2008). Its application in ecology is invaluable for forecasting potential species distributions across expansive geographic areas, offering valuable insights for conservation initiatives and decisions regarding the management of vulnerable species or the evaluation of the impact of climate change on species distributions.

This study aims to analyze the changes in the range of *C. sativa* under various climate change scenarios covering 2061–2080 within the Trabzon Regional Directorate of Forestry (RDF). To achieve this objective, we will execute the following steps: (1) conduct a comprehensive model calibration encompassing various regularization multiplier values and feature classes employing the R package Kuenm; (2) select the most suitable models based on criteria such as statistical significance, predictive capability, and model complexity; (3) develop final models for the Shared Socio-economic Pathways (SSPs) 1-2.6, 2-4.5, and 5-8.5, relying on predictions generated by the Hadley Centre Global Earth Model HadGEM3-GC31-LL; (4) calculate extrapolation risk, identify critical variables, and (5) perform map algebra to delineate changes in the current and future distribution of the species. The results will be pivotal in anticipating and planning actions to mitigate the impact of climate change on *C. sativa*, facilitating crucial adaptation strategies.

2. Materials and Methods

2.1 Species data

We conducted the modeling using the data recorded by Trabzon RDF between 2017 and 2022 (OGM, 2023). The mapped area comprises Trabzon, Rize, Gümüşhane, and Bayburt provinces (with a 5 km buffer), located in the Black Sea region (Figure 1). We reduced locally dense sampling by thinning the records to one per 1 km by 1 km grid cell. In total, a final database of 674 records was obtained. To create the models, 75% of the data was assigned for training and 25% for testing.

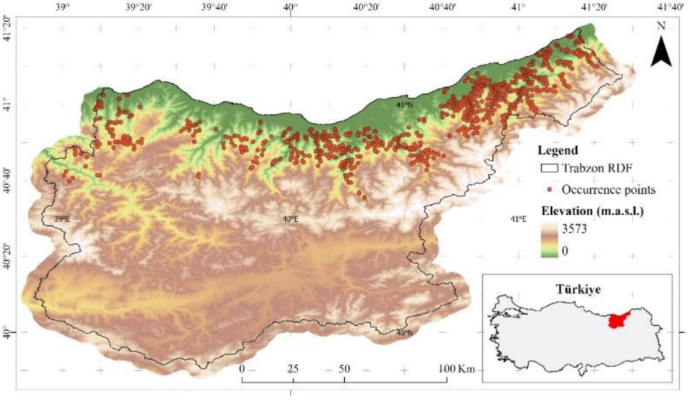

Figure 1. General location of the study area (Geographic Coordinate System WGS 1984)

2.2 Predictor variables

Eleven predictor variables related to chestnut ecology were chosen, ensuring that their pairwise Pearson correlations were below 0.80, as indicated in studies by Duran (2016), Sarikaya and Orucu (2019), and Sivrikaya and Ozcan (2023). Climate data were obtained from WorldClim v2.1 (https://www.worldclim.org/). They included annual mean temperature (bio1), maximum temperature of the warmest month (bio5), minimum temperature of the coldest month (bio6), temperature annual range (bio7), annual precipitation (bio12), precipitation of the driest month (bio14), and precipitation seasonality (bio15). The climate data correspond to 1970–2000, supplied on a 30-second (~ 1 km^2) grid. Topographic data were obtained from EarthEnv (https://www.earthenv.org/topography) and included elevation (elev), slope (slp), aspect (aspcos), and topographic position index (tpi). These data were supplied with a resolution of 1 km. The predictor variables were calibrated to a grid size of 30 x 30 m using the interpolation tool of Kriging in ArcGIS Pro-2.5.

The future projections were derived using the HadGEM3-GC31 climate models (Williams et al., 2018) under the Shared Socio-economic Pathways (SSPs) 1-2.6, 2-4.5, and 5-8.5. SSP1-2.6 assumes sustainable socioeconomic development, equity, social justice, and environmental conservation. Carbon emissions are low, and effective measures are taken to mitigate climate change. SSP2-4.5 assumes moderate economic growth and a continuation of current trends. Carbon emissions are not significantly reduced, and climate change is addressed in a limited way. SSP5-8.5 assumes development is driven primarily by fossil fuels. Carbon emissions are very high, and climate change is accelerating significantly (IPCC, 2023). These future climate layers (2061-2080) were also obtained from WorldClim v2.1 and worked at a scale of 30 x 30 m.

2.3 Niche-based models with Kuenm

434 candidate models for *C. sativa* were created by combining one set of environmental predictors, 14 regularization multiplier values (0.1-1.0 at intervals of 0.1, 2-5 at intervals of 1), and 31 feature class combinations (linear = l, quadratic = q, product = p, threshold = t, and hinge = h). The candidate models were evaluated based on significance (partial ROC, 500 iterations and 50% of the data for bootstrapping), omission rates, and model complexity (AICc). The best models were selected with the criteria of significance and omission rates ≤5%. Finally, we chose models with delta AICc values of 2 as the final models from this set.

The final model for *C. sativa* was created using the complete set of occurrences and the chosen parameterization that yielded the best model. 10 replicates were carried out through cross-validation, generating complementary log-log (cloglog) outputs for the calibration area. To project the model to future climate scenarios, we applied clamping extrapolation. The quality of this extrapolation was assessed using metrics such as multivariate similarity surface (MESS) and most dissimilar variable (MoD). MESS and MoD estimate the ability of the model to generalize beyond the calibration area to other regions or climatic conditions. To see in detail the use of the Kuenm R package, refer to Cobos et al. (2019).

2.4 Distribution range changes

To estimate the changes in the distribution ranges of C. sativa we binarized the probability maps generated using as a threshold the average of the maximum training sensitivity plus specificity (MTSS) values for each of the iterations. Then, using map algebra, the presence and absence areas in each of the climate change scenarios were calculated. Figure 2 displays the summary of the modeling approach used in this study.

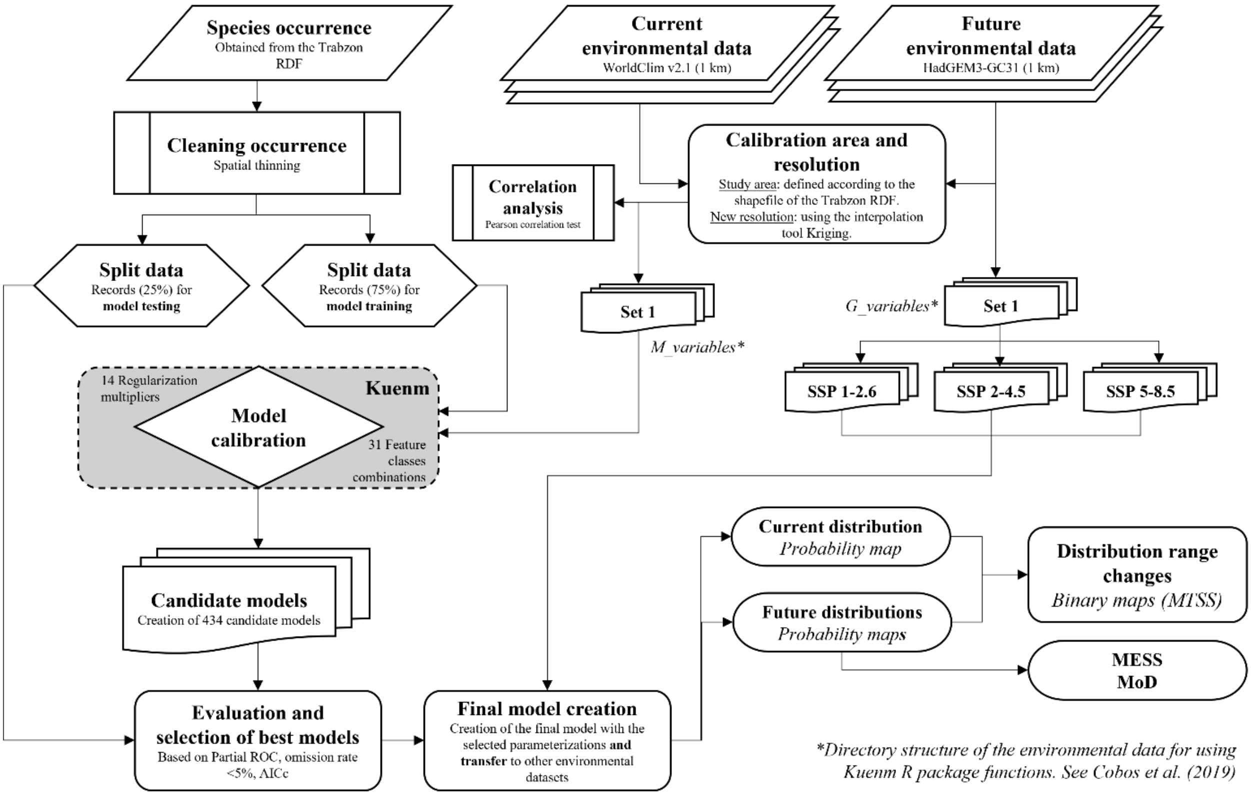

Figure 2. Flowchart summary of the modeling approach in this study

3. Results and Discussion

3.1 Current chestnut tree distributions in Trabzon RDF

Considering the three evaluation criteria of the models, the Kuenm algorithm identified the optimal configuration as a combination of quadratic and product features with a regularization multiplier set to 0.3 (Table 1). We modeled the distribution of C. sativa based on current climatic conditions and topographic characteristics in the study area. As depicted in Figure 3A, the species is predominantly located in the northern part of the Trabzon RDF, encompassing the provinces of Trabzon and Rize. The suitable areas represent 21.39% of the total study area, as illustrated in Figure 4A. Our findings are in line with previous studies on chestnut tree distributions, as reported by Sarikaya and Orucu (2019) and Metreveli et al. (2023).

According to the response curves of the predictor variables, *C. sativa* displays a higher likelihood of occurrence in regions with annual mean temperatures ranging from 8 to 15°C (bio1), capable of tolerating maximum temperatures of 32°C (bio5) and minimum temperatures of -5°C (bio6). The species can tolerate a maximum annual temperature range of 30°C (bio7), suggesting a seasonal temperature variation in the areas where it is most likely to thrive. Concerning precipitation values, *C. sativa* exhibits a preference for annual mean precipitation (bio12) levels exceeding 200 mm, with a mild precipitation seasonality (CV = 30%). Regarding altitude, the species demonstrates a high probability of occurrence across a broad elevation range (0-1500 m.a.s.l.). Concerning slope, aspect, and topographic position index values, *C. sativa* did not display a specific range of preference.

Table 1. H65 validation results for January 2021 – March 2021 over TürModel performance under optimal parameters (*) and default parameters (-), regarding regularization multiplier (RM) and feature classes (FC; l=linear, q=quadratic, p=product, t=threshold, and h=hinge) for C. *sativa*. Delta AICc of models with default settings are relative to the selected models

RM	FC	partial ROC	Omission rate 5%	AICc	Delta AICc	Weight AICc	Number of parameters
*0.3	qp	**0.00**	**0.05**	21250.47	0.00	1.00	34
-1.00	h	**0.00**	0.06	21433.36	182.89	0.00	103
-1.00	l	**0.00**	0.07	21545.34	294.87	0.00	8
-1.00	lh	**0.00**	0.06	21388.47	138.00	0.00	84
-1.00	lp	**0.00**	**0.04**	21289.76	39.29	0.00	20
-1.00	lph	**0.00**	**0.05**	21374.92	124.45	0.00	82
-1.00	lpt	**0.00**	0.10	21323.55	73.08	0.00	86
-1.00	lpth	**0.00**	0.10	21339.98	89.51	0.00	90
-1.00	lq	**0.00**	**0.05**	21320.49	70.02	0.00	14
-1.00	lqh	**0.00**	0.06	21383.12	132.65	0.00	82
-1.00	lqp	**0.00**	**0.05**	21269.72	19.25	0.00	24
-1.00	lqph	**0.00**	**0.05**	21392.96	142.49	0.00	88
-1.00	lqpt	**0.00**	0.10	21306.04	55.57	0.00	79
-1.00	lqpth	**0.00**	0.10	21316.72	66.25	0.00	82
-1.00	lqt	**0.00**	0.10	21301.94	51.47	0.00	73

Note: Bold numbers indicate final models that met the statistical significance and omission rate criteria

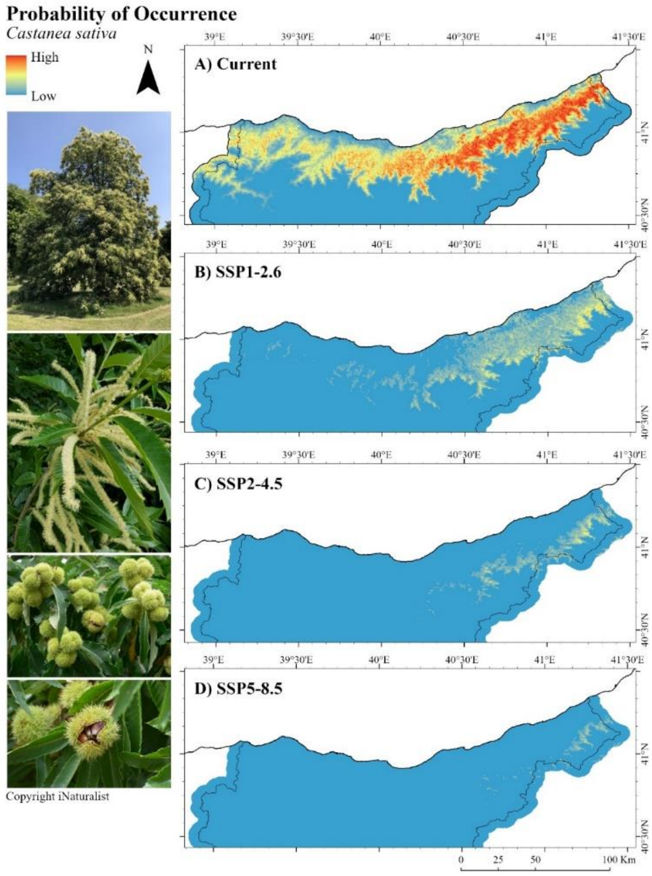

Figure 3. Current (A) and future (B-D) occurrence probability of *C. sativa*. For further detail, emphasis is placed on the provinces of Trabzon and Rize (Geographic Coordinate System WGS 1984). Orange-red colors indicate high habitat suitability, while yellow-blue colors indicate lower suitability. On the left-hand side are photographs of *C. sativa*, from tree to fruit, downloaded from iNaturalist for reference

Based on the model's results, the most important variables were precipitation of the driest month (bio14), elevation (elev), annual mean temperature (bio1), minimum temperature of the coldest month (bio6), and precipitation seasonality (bio15) (Table 2). Our results are consistent with prior research on chestnut tree distributions, exemplified by the work of Freitas et al. (2022), where they emphasize the intricate relationship between chestnut tree yield and both the total annual precipitation and its seasonal distribution. According to their findings, the augmentation of fruit size is positively influenced by summer precipitation, while winter precipitation plays a pivotal role in soil water retention, promoting the initiation of fruit setting.

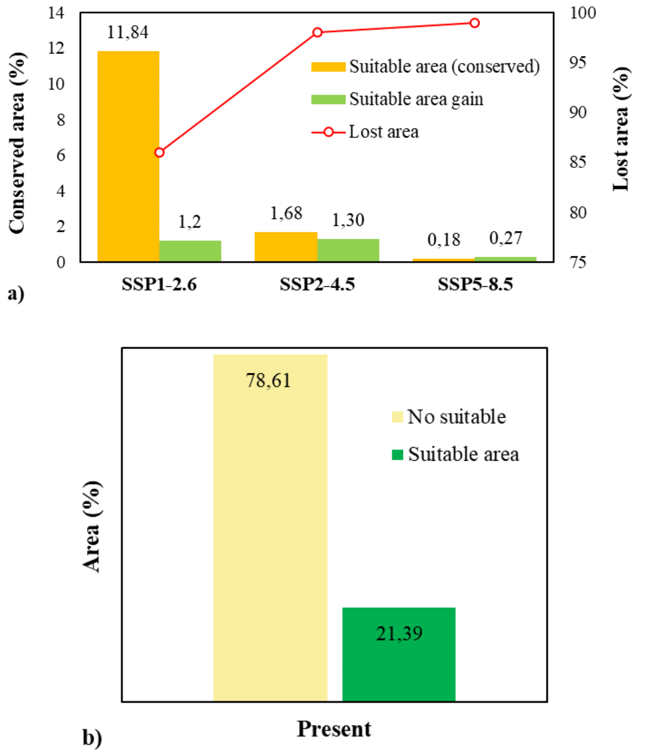

Figure 4. Habitat suitability distribution: Present (a) vs. Future (b) relative to baseline

While our study confirms the significance of elevation in chestnut tree growth, our observed tolerance range aligns with that of Freitas et al. (2021), but with a slightly difference in the upper limit. According to our results, C. sativa prefers environments with average annual temperatures between 8 and 15°C and can tolerate maximum temperatures of 32°C, findings consistent with those reported by Conedera et al. (2016). This adaptability to various thermal conditions is characteristic of a moderately thermophilic species (Gomes-Laranjo et al., 2006).

Precipitation levels play a pivotal role in the growth of C. sativa. The species demonstrates remarkable adaptability, exhibiting an extensive tolerance range for annual precipitation. However, in our study area, the preference for annual precipitation values starts from 200 mm, deviating from the range reported by Menéndez-Miguélez et al. (2015). Notably, the duration of dry periods emerges as a substantial climatic constraint on chestnut development (Conedera et al., 2021). Prolonged droughts lasting more than two consecutive months can significantly impede growth a phenomenon commonly observed in Mediterranean-type climates (Menéndez-Miguélez, 2015).

Table 2. Environmental variables selected by MaxEnt models for *C. sativa* and their permutation importance

Species	**Mean AUC ± SD**	**Variable contributions (Permutation importance)**										
		bio1	**bio5**	**bio6**	**bio7**	**bio12**	**bio14**	**bio15**	**elev**	**slp**	**aspcos**	**tpi**
C. sativa	0.91± 0.007	**15.2**	0.1	**12.7**	5.2	3.1	**32.3**	**6.9**	**19.0**	4.2	0.7	0.5

Note: The values in bold correspond to the variables that contributed more to the model according to the importance of permutation

3.2 Future chestnut tree distributions in Trabzon RDF

The pattern of SSP1-2.6, SSP2-4.5, and SSP5-8.5 shows a concerning reduction in the probability of C. sativa occurrence for the 2061–2080 period (Figure 3B-D). This will result in losses of suitable areas between 86% and 99% by 2061 (Figure 4B). According to our model, the species will shift in its geographic range in search of more suitable climatic conditions (Figure 5A-C), for which the species may progressively migrate to higher latitudes or elevations. The percentage of conserved area compared to the reference period for SSP1-2.6, SSP2-4.5, and SSP5-8.5 will be 12%, 2%, and 0.2%, respectively (Figure 4B). This reduction in habitat suitability suggests that C. sativa will face significant impacts even under the SSP1-2.6 scenario, indicating that despite substantial reductions in greenhouse gas emissions, the projected climate change poses a severe threat to the species and its current habitat.

The vulnerability of *C. sativa* in various climate change scenarios is primarily attributed to factors such as the average annual temperature and the maximum temperature during the warmest month (Figure 5D-I), both critical for the species. As noted by Freitas et al. (2021), elevated temperatures can accelerate vegetative activity, promoting the progression of phenological stages and increasing susceptibility to diseases and pests.

In our study area, under the SSP1-2.6 scenario, a 4°C increase in the average annual temperature is projected for the period 2061–2080, reaching 18°C. While this falls within the tolerable range for *C. sativa*, it signifies a shift towards more extreme summers, resulting in increased water stress and reduced survival capacity. Presently, the maximum temperature during the warmest month stands at 31°C. However, under the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios, temperatures of 36°C, 37°C, and 40°C, respectively, are projected to be reached. These elevated temperatures are expected to induce thermoinhibition as they surpass the critical threshold of 32°C, previously identified as the trigger for this process (Gomes-Laranjo et al., 2009; Pereira et al., 2011). Furthermore, the tree appears particularly susceptible to heightened water stress and an increased risk of mortality during periods of drought (Conedera et al., 2021).

The projected reduction in habitat suitability for *C. sativa* aligns with findings from previous studies on the impact of climate change on the species. For instance, Atalay Dutucu (2023) modeled the distribution of *C. sativa* in the Anatolia region and its surroundings for the period 2081-2100. According to the results, a decrease in habitat suitability is anticipated in the Black Sea region, which currently boasts one of the highest levels of habitat suitability, particularly in the SSP2-4.5 and SSP5-8.5 scenarios. Analyses by Sarikaya and Orucu (2019) predict that the habitat for *C. sativa* will decline in the future, and potential losses under both climate change scenarios (RCP4.5 and RCP8.5 for 2050-2070) may reach critical proportions.

Moreover, additional studies, such as those conducted by Perez-Giron et al. (2020) in Switzerland and Conedera et al. (2021) in the Iberian Peninsula, underscore that chestnut is not inherently prepared for the future. This is due to expected increases in summer temperatures and dry periods, particularly in xeric site conditions. Furthermore, there is a substantial risk that the species may be seriously affected or even face the threat of disappearance.

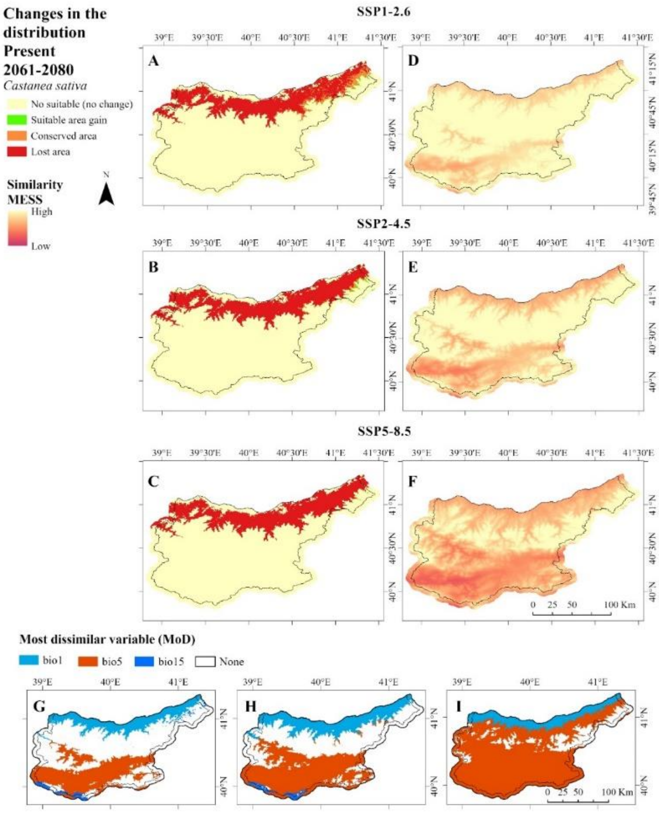

Figure 5. Changes in the distribution of *C. sativa*. Comparisons from the present to 2061-2080 (A-C). The threshold established for binarization of the probability maps was 0.226. MESS maps (Multivariate Similarity Surface) highlight the difference between current and future conditions under various climate change scenarios. Reddish colors indicate more significant dissimilarity, while yellow colors indicate that there is not a significant change in climatic conditions (D-F). On the other hand, MoD maps (G-I) depict the variables that most influence the difference in future environmental conditions in the study area

4. Conclusions

In this study, we assessed the impacts of climate change on the distribution of C. sativa in the Trabzon RDF using the ecological niche modeling approach. Our findings suggest that climate change may significantly diminish the habitat suitability for C. sativa, even under the SSP1-2.6 scenario. This poses a substantial risk to the species, impacting not only ecosystems but also socio-economic aspects related to chestnut fruit harvesting.

The methodology employed in this study, particularly the use of tools like Kuenm, holds significance for creating statistically robust models that generalize well to new data and avoid overfitting to training data, especially when considering transfers to new climatic conditions. Additionally, it facilitates a more in-depth analysis by incorporating metrics such as MESS and MoD.

To assist the species in confronting these long-term challenges (2061-2080), the implementation of active conservation measures may be necessary. These measures could include critical habitat protection and reintroduction into more suitable areas. Furthermore, it is crucial to maintain continuous monitoring of the species' distribution, population, and potential diseases as climate change progresses. This ongoing observation will provide valuable data for assessing the species' response and the effectiveness of conservation efforts.

By implementing actions to mitigate climate change and employing effective conservation strategies, we can enhance the species' capacity to adapt to a changing environment.

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