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Potential effects of climate change on future distribution of an endangered tree species, *Acer mazandaranicum,* in the Hyrcanian forest

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A R T I C L E I N F O

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A B S T R A C T

Acer mazandaranicum is an endemic, endangered, recently described large tree species distributed in the Hyrcanian forest. Only a few scattered populations with low density are known in the Alborz Mountains of Iran. This research aims to approximate the potential geographical distribution range of *A. mazandaranicum* in the past, present, and future to provide a basis for prioritizing conservation-related activities. For the contemporary climate model, two past scenarios and three future climate scenarios were tested. The most crucial variables, as determined by the model, were the seasonality of precipitation and the amount of precipitation during the driest quarter, which together constituted 90.9% of the model for current conditions and presented *A. mazandaranicum* climatic requirements for appropriate habitats. According to our findings, the potential habitat of the species will be drastically diminished in suitability in the future. The model projected an area of 7410.8 km^2 as moderate suitability habitat (0.50–0.75) and 13,896.41 km^2 as low suitability (0.25–0.50). The average altitude in the potential range is 1026 m a.s.l. During the LGM, the potential range of *A. mazandaranicum* was 209.27% of the current area and spread mainly at lower altitudes (1078.8 m a.s.l.). The findings indicate a fascinating possibility that the species may possess the capability to shift their altitudinal distribution and potentially migrate to higher elevations in response to increasing temperatures and decreasing rainfall. According to morphological spatial analysis (MSPA), the central and western regions of the Hyrcanian forests contain a core area with high connectivity. In order to mitigate the threats facing this endangered species and reduce the risk of extinction, ex situ conservation measures as well as in situ protection activities within their habitats are necessary for ensuring its long-term survival.

1. Introduction

The ecological niche availability and dispersal potential of plant species at various geographical scales depends on several drivers of global biodiversity, such as climate, biological interactions, soil characteristics, land use, and topography (Abolmaali et al., 2018). Climate is expected to be the most effective factor influencing biodiversity, species survival and species geographical distribution range across wide spatial scales (Leng et al., 2008; Keane et al., 2020). Climate-driven global environmental variation profoundly affected the geographical distribution range and abundance of plans, especially for species that have distinct ecological requirements and limited geographic ranges composed of small, isolated populations (Abdelaal et al., 2019; Song et al., 2019; Anderson et al., 2023). Distributional alterations in current plant species have been seriously influenced by climate fluctuation during paleoclimate conditions. An efficient way to determine the regions where species would be distributed in response to future climate change involves forecasting the relationships between plants' dynamic change and past climate circumstances (Su et al., 2021a; Cong et al., 2020). In light of studies on threats associated with climate change and

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their variation through the landscape, the expansion of protected regions and conservation strategies are crucial solutions related to the escalating depletion of biodiversity and climatic shifts in species geographical distribution ranges (Wei et al., 2018; Grumbine and Xu, 2021; Stralberg et al., 2020). Since unfavorable climatic conditions can amplify species local extinction rates, reduced biodiversity, loss of ecosystem resilience and result in dwindling suitable habitats (Milad et al., 2011; Birhane et al., 2020; Keane et al., 2020; Khanal et al., 2022), conservationists are currently involved in efforts to analyze the consequences of climate variation on the spreading of different plant species to boost model simulations of forest survival and expansion (Muller et al., 2019; Gerassis et al., 2021; Mkala et al., 2022). To achieve this, a species distribution model is being utilized to determine the potential geographic range and extent of occurrence of higher-risk threatened plants, as an essential step in the direction of formulation of effective conservation techniques (Mir et al., 2020; Pant et al., 2021; Liu et al., 2022a).

Several scenarios on climate change predict that the global temperature is projected to increase continuously in the foreseeable future and could potentially reach a level ranging from a minimum of 0.3–1.7 °C to a maximum of 2.6–4.8 °C at the end of the year 2100 (Wei et al., 2018; Zhao et al., 2020). The implications of this trend are likely to encompass a universal shift in species distribution, especially for tree species whose present northerly boundaries of occurrence are bound to shift and have the northernmost point of occurrence (Boisvert-Marsh and de Blois, 2021; Koide et al., 2022). It is reported that, worldwide species geographical distribution range have shifted to higher elevations and latitudes at a median rate of 11.0 m and 16.9 km, respectively, per decade (Keane et al., 2020). There is significant evidence indicating that, towards the end of the century, the temperature in the Middle East will likely face an increase of over 4 °C and a reduction in rainfall of around 20% (Elasha, 2010). Among the Middle East countries, Iran experiences more severe climate change effects than other regions, while in the final years of the century, Iran is anticipated to experience a rise in temperature by 2.6 °C, a decrease in precipitation by 35%, and a surge in heat waves by around 30%. (Rahimzadeh et al., 2009; IPCC, 2012; Mansouri Daneshvar et al., 2019). Currently, regional or local extinction rates of species are approximately 1000 times higher than in the past due to the loss or degradation of suitable habitat and its consequences, including changes in functional diversity, community structure, and species richness (Pimm et al., 2014; Roy et al., 2022). Based on climate-warming scenarios for 2050, projections of species distribution estimate that approximately 15% to 37% of the species in sampled regions, which encompass 20% of the planet's terrestrial surface, will be in danger of becoming extinct (Thomas et al., 2004; Su et al., 2021a). On the other hand, human activities, such as burning fossil fuels, producing and using fertilizer, overexploiting natural resources, destroying habitats, deforesting, urbanizing, and industrializing are contributing to the acceleration of climate change. These interventions cause an increase in the release of greenhouse gases, especially carbon dioxide. As a result, the Earth's climate is changing, and temperatures are rising on average (Rustad et al., 2012). Globally, narrow distribution ranges, human interventions, and climate change cause potential endangerment and extinction of plant species at accelerating rates (Ren et al., 2012) and the species habitat index has experienced a decline of 2% in recent decades (Ye et al., 2021). The International Union for Conservation of Nature (IUCN) reports that approximately 6.7% of known vascular plant species are endangered (Ren et al., 2014).

Acer mazandaranicum Amini, Zare and Assadi is a recently described, large tree species that belongs to the Sapindaceae family and is endemic to the southeastern Hyrcanian forests (Fig. 1) (Amini et al., 2008). The species generally favors humid, foggy, and high-elevation northern slope habitats that have an elevation between 1500 to 1900 m above sea level (Amini et al., 2008). These particular habitats experience a mean annual rainfall of 500 to 900 mm and an average temperature that varies between 11 to 17 °C throughout the year (Mohtashamian et al., 2017). *A. mazandaranicum* is classified as a critically endangered species based on the IUCN Red List criteria and categories. This designation is due to the species having a very limited area of occupancy (AOO) measuring only 12 km^2 and small extent of occurrence (EOO) that spans just 28 km^2 (Mohtashamian et al., 2017).

Accurate information regarding the precise information about the exact locations where a particular species can be found is crucial for effective conservation planning. However, the distributions of rare and threatened species are often incomplete due to the limited distribution data collected over a long time-scale, combined with unreliable spatial accuracy (Brunton et al., 2023). Thus, any efforts aimed at improving the accuracy and completeness of the available information, such as the use of species distribution modeling for assessing the appropriateness of a habitat for a particular species, can lead to a more comprehensive understanding of their distribution range. This can result in improved conservation efforts and administrative decisions for these species (Ramirez-Reyes et al., 2021). A fundamental understanding of a species' geographical distribution pattern and its relation to constraining climatic variables is one of the basic components in assessing the level of risk a species faces and determining the need for conservation efforts (Kujala et al., 2018).

SDM, or species distribution modeling, is a valuable technique that helps in determining the likelihood of a certain species being present in a specific geographic location and assessing its potentially suitable habitats as well as its geographic distribution patterns, by analyzing relevant environmental variables (Pecchi et al., 2019; He et al., 2020; Liu et al., 2022a; Eduardo et al., 2022; Baou et al., 2023). SDM models can also be used to determine the potential habitat range of a species, which can be

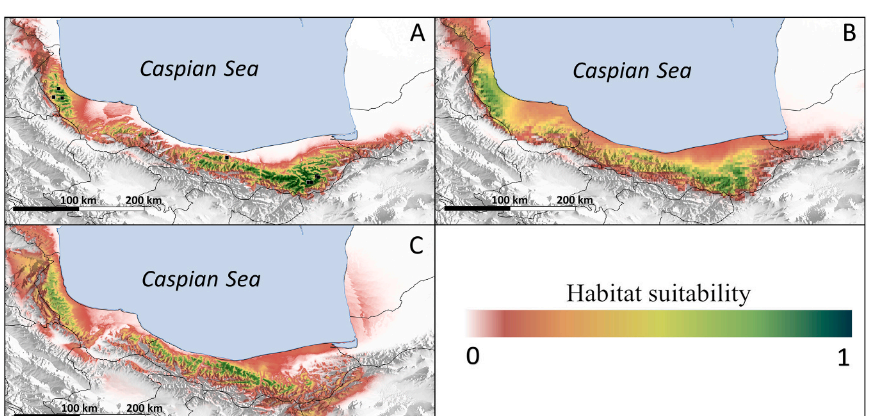

Fig. 1. Predicted habitat suitability patterns of *A. mazandaranicum* under current and past climatic conditions. A) current range with 34 species occurrence records in North of Iran (black dots), B), Last Glacial Maximum C) Late Holocene. The highest and lowest suitability are perceived as green and red colors, respectively.

used to estimate its EOO as a crucial parameter for assessing extinction risk and informing IUCN Red List assessments (Breiner et al., 2017).

Maximum entropy modeling (MaxEnt), developed by Phillips et al. in 2006, is one of the most popular SDM methods because it can effectively handle presence-only data and performs reliably even when the sample size modeling data is small and species distribution data is incomplete (Elith et al., 2006; Qin et al., 2017, Xu et al., 2019; Kaky et al., 2020; Choi and Lee, 2022). MaxEnt is performing well (Elith et al., 2006; Hernandez et al., 2006; Radosavljevic and Anderson, 2014; Smith et al., 2021), have high prediction accuracy and versatility for rare species, narrowly endemic species, and those facing the risk of extinction (Williams et al., 2009; Rhoden et al., 2017; Ye et al., 2022; Barber et al., 2022). However, its output depends critically on model complexity and how closely data match assumptions (Phillips and Dudík, 2008; Elith et al., 2011; Anderson and Gonzalez, 2011; Warren and Seifert, 2011).

The SDM statistical algorithm was utilized in the present study, resulting in the achievement of the subsequent objectives: (1) to evaluate the existing distribution of *A. mazandaranicum* in the Hyrcanian forests; (2) To anticipate the future geographical range of this particular species in response to varying climatic conditions; (3) To trace the history of the species range and see which stands may be located in climatic refugia and (4) To explore the principal climate-related factors that affect the spread of this particular species. We expect that the outcome of our research will establish a fundamental basis for determining the priority ranking of preservation initiatives that target *A. mazandaranicum* as an endangered tree species in the Hyrcanian forest.

2. Material and methods

2.1. Study area

The Hyrcanian Forest Region located in Iran and a portion of Azerbaijan, situated within the Euro-Siberian region, is a geographically elongated and slender tract of land that ranges from 20 to 110 kilometers in width, spanning a length of over 800 kilometers. The geographic location of the area is nestled between the southern coast of the Caspian Sea, which is known as the largest lake in the world, and Iran's Alborz Mountains (Sagheb Talebi et al., 2014; Homami Totmaj et al., 2021). This geographically and climatically diverse region, which rises from the lowland to > 2000 m above sea level, encompassing widespread of deciduous species, within which a noticeable presence of Arcto-Tertiary relict components can be discerned (Ghorbanalizadeh and Akhani, 2022; Akhani et al., 2010). According to climate records, the Caspian coastline exhibits an average annual precipitation range from 530 mm in the eastern region to 1350 mm, occasionally exceeding 2000 mm, in the western region. Additionally, the temperature in this area changes depending on the location, with the western region having an average annual temperature of 15 °C and the eastern region having a slightly higher average temperature of 17.5 °C (Taleshi et al., 2019; Ahmadi et al., 2020., Yousefzadeh et al., 2022). The Hyrcanian region boasts exceptional floristic biodiversity, including 3855 documented vascular plants. Additionally, 256 out of 3855 (6.6%) species having a place to 152 genera and 50 families are endemic and subendemic to the Hyrcanian region (Ghorbanalizadeh and Akhani, 2022).

2.2. Occurrence points

Locations of *A. mazandaranicum* stands and individuals were collected during field trips (2019–2022), as well as from the IUCN database (Barstow and Crowley, 2018) and literature (Amini et al., 2008). It should be explained that only a few populations of this species with a very small number have been identified in the Hyrcanian forest so far. A total of 34 points were collected, but due to the small area the species occupies and the proximity of the points, part of them were discarded by the MaxEnt; eventually, only 11 were used to create models. This restricted number of locations should be sufficient to create a valid model for a rare species with a small number of stands (Hernandez et al., 2006, van Proosdij et al., 2016).

2.3. Climatic variables

A set of bioclimatic variables for current conditions was downloaded from the CHELSA database (Karger et al., 2017, 2018). In addition to the contemporary climate model, two past scenarios (Last Glacial Maximum – LGM, approximately 21 ka BP, and Late Holocene - LH, 4.2–0.3 ka BP) and two future climate scenarios (Representative Concentration Pathway (RCP) 4.5, and RCP 8.5; Gent et al., 2011; Collins et al., 2013) were tested. Rasters of bioclimatic variables for LH were downloaded from the PaleoClim database (Fordham et al., 2017; Brown et al., 2018), and those for the remaining scenarios were downloaded from the CHELSA database (Karger et al., 2017, 2018). To reduce collinearity between variables, Pearson correlations were calculated using the layerStats function from the package 'raster' in R (Hijmans and van Etten, 2012; RCore Team 2023). The remaining 10 uncorrelated rasters (bio2, bio4, bio5, bio6, bio8, bio9, bio10, bio12, bio15, and bio17) were used for creating models.

2.4. Model building

The potential range of species was estimated using MaxEnt 3.4.1 software (Phillips et al., 2006, 2019). The analysis parameters were optimized using the ENMeval package in the R environment (Muscarella et al., 2014). The final analyses were conducted using the model with the lowest AIC value (Table S1). Each analysis was run as a bootstrap with logistic output, linear-quadratic features, 0.5 regularization multiplier, a convergence threshold of 10^{-5}, 750 background points, 10, 000 maximum iterations, and 100 replications. A "random seed" option was used to provide a random test partition; for each replication, 9 presence records were used for training and 2 for testing. To remove the spatial bias, the bias file was created using known locations of several tree species from Hyrcanian region (Fig. S1) according to literature (Alipour et al., 2023; Alipour and Walas, 2023; Browicz, 1982; Gholizadeh et al., 2019; Ghorbanalizadeh and Akhani, 2022; Mohtashamian et al., 2017; Yousefzadeh et al., 2022).

2.5. Model evaluation

Receiver operating characteristic (ROC), area under the curve (AUC) and true skill statistics (TSS) were used to test the accuracy of the model (Allouche et al., 2006; Wang et al., 2007; Mas et al., 2013). MaxEnt results were visualized in QGIS 3.16.4 'Hanover' (QGIS Development Team, 2020). The same software was used to calculate the area of the potential range and the average altitude. Suitable area was divided into three classes: low suitability (0.25–0.50), moderate suitability (0.50–0.75) and high suitability (above 0.75). Additionally, there were created binary maps with "maximum test sensitivity + specificity" as a threshold (Fig S2).

2.6. MSPA analysis

GuidosToolbox was used for morphological-spatial analysis (MSPA), which allows the measurement of the potential range structure (Soille and Vogt, 2009; Soille and Vogt, 2022; Vogt and Riitters, 2017). The MSPA is a quantitative method focusing on describing the morphology and connectivity of landscapes using morphological calculations based on the Euclidean distance threshold between grid cells. The MSPA divides binary grid images into seven categories: Core, Islet, Perforation, Edge, Bridge, Loop, and Branch, each with specific ecological meanings. This widely-used method allows to analyze landscapes through numerical representation (Kang and Kim, 2015; Sudhakar et al., 2018; Wang et al., 2020; Huang et al., 2021; Wang et al., 2022). The input raster for this analysis were the results of MaxEnt for current and future climatic conditions. The threshold value was suitability 0.25.

3. Results

3.1. Evaluation of models and variable contribution

All models were characterized by high AUC values between 0.973 and 0.982, as well as high TSS values between 0.890 and 0.984 (Table 1). According to the model, the most important factors were precipitation seasonality (bio15) and precipitation of the driest quarter (bio17), which together constituted 90.9% of the model for current conditions; also, minimal temperature of coldest month (bio6) and mean temperature of wettest quarter (bio8) show significance in tested models (Table 1).

3.2. Current potential distribution

The current potential range of *A. mazandaranicum* covers a large part of the Hyrcanian area by a total of approximately 24,338.82 km^2 (Table 2). Approximately 3031.61 km^2 constitute areas that were estimated as high suitability habitats (>0.75), located in the northern part of Gilan and the mountainous region of southeastern Mazandaran (Fig. 2A). The model projected an area of 7410.8 km^2 as moderate suitability habitat (0.50–0.75) and 13,896.41 km^2 as low suitability (0.25–0.50). The average altitude in the potential range was 1451.15 m a.s.l. (Table 2).

3.3. Past potential distribution

During the LGM, the potential range of *A. mazandaranicum* was 209.27% of the current area and spread mainly at lower altitudes (1078.80 m a.s.l.). Out of the total range (50,934.83 km^2), 1000.39 km^2 was estimated as a high-suitability habitat with the possibility of potential as refugia during the LGM. These were located in: 1) Mazandaran, where the coastal areas were more suitable than the mountains, and 2) Gilan, where the suitability range pattern of the area was similar to the current potential range. The main barrier between these areas was the lowlands near the modern city of Rasht. In the late Holocene, the potential range of species resembled the modern range with 1087.58 km^2 of the highly suitable area (Table 2).

3.4. Future potential distribution

It was apparent that the potential habitat suitability of the species will shrink significantly in the future. In the tested two scenarios, reduction in the range of the species was clear; total area of suitable habitats was predicted in RCP 4.5 as 6711.53 km^2 and in RCP 8.5 565.31 km^2 (Fig. 3; Table 2). The stable of range has occupied the westernmost part of Gilan toward the Talish mountains and Azerbaijan. Interestingly, the results showed that the species may shift

Table 1
Contribution significantly of bioclimatic variables, area under the curve (AUC) index, and TSS in the tested models of the distribution of *A. mazandaranicum*.

Tested scenario	Bioclimatic variable				AUC	TSS
	Bio15	Bio17	Bio6	Bio8		
Current	**76.8**	**14.1**	**2.2**	**3.2**	0.973	0.968
LH	**79.6**	**7.8**	**5.7**	**3.1**	0.981	0.984
LGM	**51.7**	**14.0**	**10.5**	**12.5**	0.982	0.890
RCP4.5	**61.3**	**13.6**	**10.2**	**7.2**	0.977	0.971
RCP8.5	**56.6**	**14.4**	**13.3**	**13.1**	0.978	0.979

Bio15: Precipitation seasonality (coefficient of variation: mean/SD * 100) [%]; Bio 17: Precipitation amount in the driest year quarter; Bio6: Min Temperature of coldest month; Bio8: Mean Temperature of wettest quarter

Table 2
Potential area, classification ranges, and average altitude according to the tested scenarios.

Tested scenario	Suitability (km2)	Stability range (km2)	Potential range (%)	Average Altitude (m a.s.l.)								
	Low (0.25-0.50)	Moderate (0.50-0.75)	High (>0.75)	Total	% of current area	Gain	Stable	Loss	Gain	Stable	Loss	
Current	13 896.41	7 410.80	3 031.61	24 338.82	100.00							1451.15
LH	14 190.32	7 631.77	1 087.58	22 909.67	94.13							1057.88
LGM	35 972.93	13 961.51	1 000.39	50 934.83	209.27							1078.8
RCP4.5	5 642.92	757.45	311.16	6 711.53	27.58	386.97	6 324.56	17 627.29	1.59%	25.99%	72.42%	1559.51
RCP8.5	565.31	0.00	0.00	565.31	2.32	15.71	549.60	23 773.51	0.06%	2.26%	97.68%	1362.86

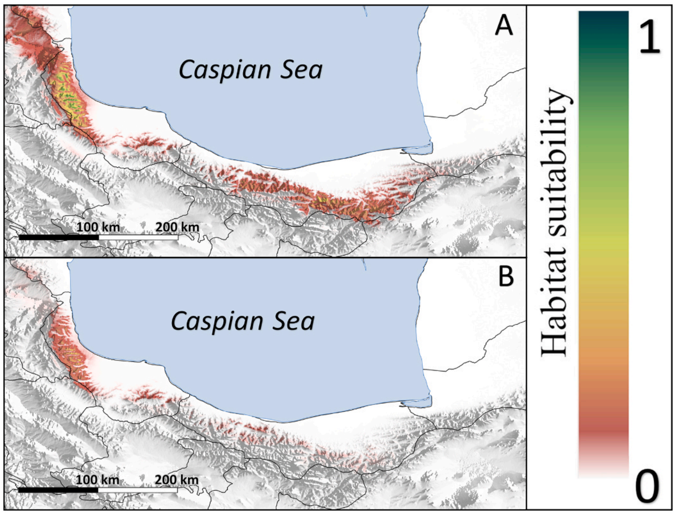

Fig. 2. Future potential distribution of *A. mazandaranicum* under future climatic conditions. future scenarios (A - RCP 4.5; B- RCP 8.5). The highest and lowest suitability are perceived as green and red colors, respectively.

in the vertical range to higher altitudes, connected with rising temperatures and decreasing precipitation (Table 2). In contrast, in the central Hyrcanian forests, particularly in the Mazandaran region, there are far fewer forests, and they decrease sharply (Fig. 4). Almost whole potential range disappear in RCP 8.5 scenario (97.68%; Fig. 3; Table 2).

3.5. Landscape connectivity

Morphological spatial analysis (MSPA) providing potential connectivity and future distributions of *A. mazandaranicum* and changes in linear elements are presented in Fig. 4 and Table 3. According to the tested models, currently, the core area with high connectivity is distributed throughout the western (Gilan) and central Hyrcanian forests (Mazandaran) (18,390.72 km^2). In RCP4.5, a remarkable portion of core areas dropped and was extremely scattered, leading to difficulty in connecting the west and center of the Hyrcanian forest. This scenario shows that one core area is concentrated in the westernmost part of Gilan, and very narrow, small, fragmented, and dispersed cores without a continuous spatial pattern are present in Mazandaran, especially in the southern part. Under RCP8.5, suitable habitats of *A. mazandaranicum* undergo striking changes and the lowest value was detected, which indicates that the highest levels of fragmentation have occurred (Fig. 4; Table 3). According to this scenario, there is no more constancy and concentrated core area across the Hyrcanian forest. Except in the westernmost part of Gilan, bridges, loops, islets, and branches were scattered, the perforation amount was zero, and there was no structural corridor connectivity among them (Table 3).

4. Discussion

4.1. Model accuracy and species relation to climate variation

This research involved forecasting the potential areas where *A. mazandaranicum* could thrive based on its climate-related habitat requirements. The models were built by utilizing information on *A. mazandaranicum*'s geographical presence as well as the environmental factors that were found to impact its survival and growth. This indicates highly accurate model performance and the closest model simulation to the real situation (Phillips and Dudík, 2008). This is similar to studies that have been conducted on the distribution patterns of *Acer* species under climate change conditions (Su et al., 2021b; Liu et al., 2022a). There are seven distinct species of Hyrcanian maples, namely *A. velutinum*, *A. hyrcanum*, *A. mazandaranicum*, *A. monspessulanum*, *A. campestre*, *A. cappadocicum*, and *A. platanoides*. Each of these species has its own unique ecological distribution range that is determined by elevation, temperature, and moisture (Mohtashamian et al., 2017). *A. mazandaranicum* is typically found in habitats that are situated at elevations ranging from 1500 to 1900 m above sea level. Moreover, it tends to thrive in areas with an average annual precipitation range of 1500 to 1900 mm and a mean temperature between approximately 11–17 °C throughout the year. Our model showed that *A. mazandaranicum* is predominantly concentrated in areas with favorable conditions that are situated in the northern part of Gilan and the mountainous region of southeastern Mazandaran. Larger shifts for mountainous plant species show that in high-altitude regions they are at greater risk from the effects of climate change compared to those in plain areas (Lenoir et al., 2008). This is probably due to the low temperature (Pauli et al., 2007) and more expeditious rise in temperature in high-elevation areas, which lead to plant species shifting to higher elevations, where there may be a significant decrease in the range of these plants and their local extinction in response to a warming climate (Engler et al., 2011; Freeman et al., 2018; Rumpf et al., 2019). The effectiveness of the predictive model in differentiating between areas where a species is expanding and those where it is not present was evaluated by AUC statistics (Kabaš et al., 2014).

The MaxEnt results showed that precipitation seasonality and the quantity of precipitation in the driest quarter were the primary factors

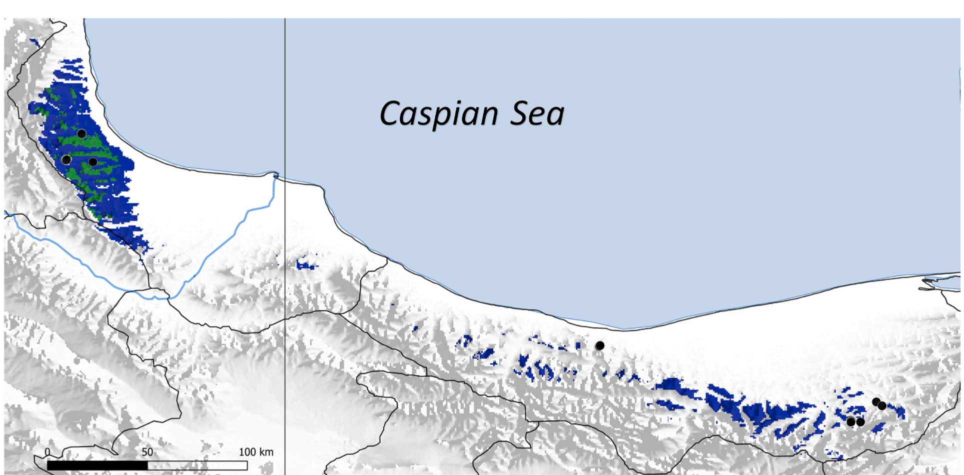

Fig. 3. Climatically stable areas with suitability higher than 0.25 in all tested models (green color) and all models except RCP 8.5 (blue color).

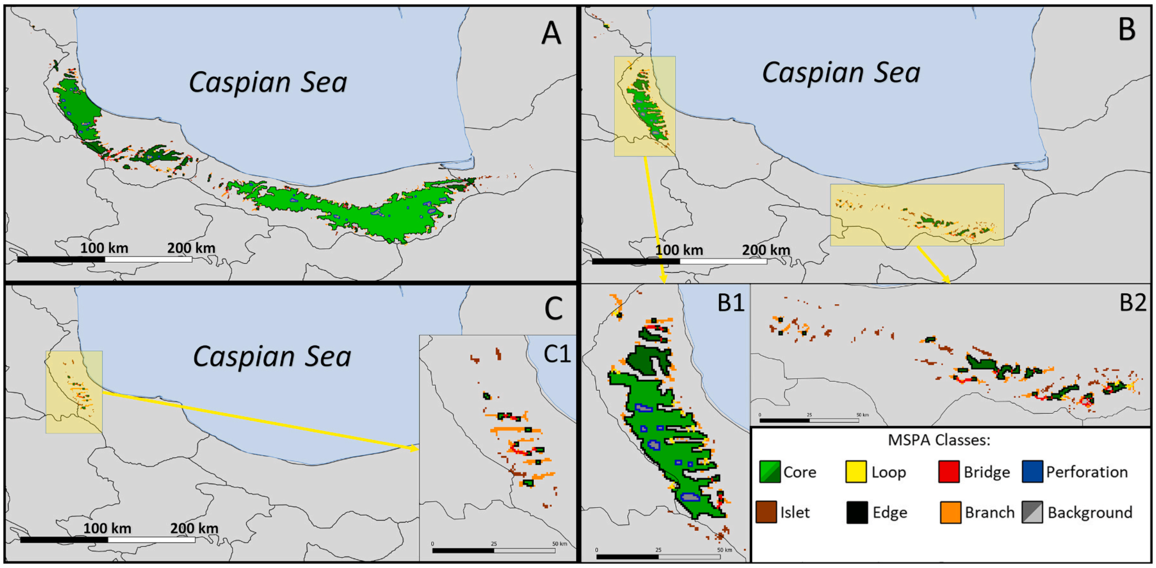

Fig. 4. MASPA categories in the habitats of *A. mazandaranicum* under current (A) and future scenarios; RCP 4.5 (B; magnifications: B1 – Gilan, B2 - Mazandaran), RCP 8.5 (C; magnification: C1 – Gilan).

Table 3
The potential area of particular classes in MSPA analysis for the area with suitability above 0.25.

Tested scenario	Area (km2)							
	Core	Loop	Bridge	Islet	Edge	Branch	Perforation	Total
Current	18 390.72	319.07	143.11	165.70	4025.43	722.38	572.42	24 338.83
RCP4.5	3934.03	119.76	86.34	356.50	1693.38	493.67	27.85	6711.53
RCP8.5	124.24	15.18	44.87	65.57	203.62	111.82	0.00	565.31

influencing the potential geographic distribution of threatened *A. mazandaranicum,* which together constitute 90.9% of the model. Our findings are consistent with previous studies on species distribution modeling of four other maple species, which indicated that variables associated with annual and seasonal fluctuations in temperature and precipitation, particularly during dry and warm periods, are the most significant limiting factors influencing the distribution patterns of *Acer* species (Kabaš et al., 2014).

It has been predicted that the climate in the forests located in northern Iran will become warmer towards the end of this century (Azizi and Roshani, 2008) and this change will be accompanied by an estimated decrease of approximately 9% in precipitation (Babaeian et al., 2010) throughout the country. It is expected that as a result of global environmental changes, plant species in the Hyrcanian forest will likely experience a reduction in their geographical range accompanied by a northward shift in species distribution and/or movement in the direction of higher altitudes (Noroozi et al., 2018; Limaki et al., 2021; Mahmoodi et al., 2023). Furthermore, a study by Liu et al. (2022b) on the potential geographic distribution of *Acer cordatum* predicted that precipitation during the driest month and precipitation seasonality were significant climatic factors that impacted the species' spread in its habitat. It has been reported that seed yield, growth features, phenological phases, and plant biomass accumulation in *Acer* species are adversely affected by precipitation regimes, which results in changes in the geographical range of species distribution and ecological adaptation (Jia et al., 2017; Su et al., 2021b).

Regarding the LGM model, the potential distribution range of *A. mazandaranicum* was 208.45% of the current area and spread mainly at lower altitudes than present, with a mean elevation of 1078.8 m a.s.l. Only 14,961.9 km^2 of the total potential range of *A. mazandaranicum* was estimated as a high-suitability habitat, which can be considered a climate refugium for this plant species. The increase in altitude of species' geographical range regarding climate change is in accordance with the fact that most plants have a tendency to migrate and shift their geographical range towards higher elevations with more suitable climatic conditions in an overall upward trend to address climate change, especially warming (Dyderski et al., 2018; Liang et al., 2018; Taleshi et al., 2019; Limaki et al., 2021; Mahmoodi et al., 2023).

In our study, climate change prediction under different scenarios showed a serious shift and decline in the suitability of *A. mazandaranicum*'s potential habitat in the coming years. According to our findings, under the most optimistic RCP 2.6 scenario, there won't be any disturbance to the species' suitable area of *A. mazandaranicum*. However, under the less favorable RCP 4.5 and RCP 8.5 scenarios, approximately 56% and 91% of the Existing suitable areas are predicted to vanish, respectively. A study Carried out by Aouinti et al. (2022) suggests that the *A. monspessulanum* potential habitat suitability will experience a significant decline of more than 99% in the future under the RCP 8.5 scenario for the duration of time between 2060 and 2080. Similarly, the results of previous studies predicted at least 70% losses in suitable habitats of the genus *Acer* in Hyrcanian forests under RCP 4.5 and more than 83% shrinkage under RCP 8.5 by 2070 (Taleshi et al., 2019). The most significant loss of suitability under the RCP 8.5 scenario observed in the present investigation is similar to what had been observed in previous studies of various plant species on a global scale. (Buras and Menzel, 2019; Soilhi et al., 2022; Fyllas et al., 2022, Khan et al., 2022). Additionally, the highest extent of stability has occupied the westernmost part of Gilan toward the Talish mountains and Azerbaijan, with an upward shift of species to higher altitudes. However, in the central Hyrcanian forest, particularly in Mazandaran Province, stability declines dramatically. Changes toward a warmer and drier climate across the entire width of the Hyrcanian forest from the eastern part of this region to its western part (Sagheb Talebi et al., 2014) would probably be more harmful to the geographical range of species in the eastern regions of the forest (Alavi et al., 2019).

4.2. Model limitations

Except for climatic variables, there are several other environmental elements that play a crucial role in the spread of plant species, and ignoring these factors is one of the main limitations of the model used in this research. Studies have demonstrated that factors such as soil composition, aboveground and root competition of plants, biotic interactions, slope orientation, and solar radiation are all among the diverse elements that greatly influence the dispersion of plant species (Guisan and Zimmermann, 2000; Lamb et al., 2009; Márquez et al., 2011; Ma et al., 2018; Alon and Sternberg, 2019). According to reports, slope orientation in different environments induces differences in available light for plants, causing alterations in temperature and soil moisture and thus influencing plant distribution (Pablo et al., 2019). Additionally, fluctuations in solar radiation can greatly affect the geographic distribution of plant species, as it is a crucial factor for various processes such as photosynthesis, the maturation of plant tissues, and transpiration (Ren et al., 2016). Also, the small number of presence points can also be effective in determining the accuracy of the results. A small number of records can lead to an incorrect model, both overestimating the range (if particular stands occur in very different conditions) and unduly limiting it (if all locations are grouped in one place). However, MaxEnt is able to create a good model even on a small number of observations (a minimum of 3 for a virtual species and 6 for a real one, van Proosdij et al., 2016). In the case of such rare species, modeling results should be approached very carefully. In the work presented here, to minimize bias, we used all known locations of the species and selected optimal parameters using the ENMeval package. Nonetheless, the presented potential range of the species is probably an overestimation, as the different sites were located in different conditions at a distance from each other and a clear core of species' real range could not be distinguished. The significant outcomes resulting from dramatic increases in human populations and disturbances are higher habitat degradation, unprincipled land use, disturbance of natural ecosystems, and overexploitation, which can lead to the elimination of plant species, notably along coastal areas (Le Roux et al., 2019), like the Hyrcanian forest region (Alavi et al., 2019).

4.3. Management implications

The repercussions of climate alteration on biodiversity and ecosystem function are significant and pose unprecedented challenges to the preservation of natural landscapes (Morelli et al., 2020; Balantic et al., 2021). Refugia from climate change, like the Hyrcanian forests, act as a protective measure against the impacts of current climate change and help ensure the continued existence of vital ecosystems, habitats, and species over an extended period (Morelli et al., 2017; Barrows et al., 2020). One valuable approach for accurate projections of where the species may be present in the future is through species distribution modeling (SDM), which uses both georeferenced observations of species occurrence and multiple environmental predictors (Gadsden et al., 2023). GIS techniques combined with SDMs are useful means for establishing protected areas based on which decision-making can be made (Khwarahm, 2020; Hama and Khwarahm, 2023). In addition, this model can be applied to managing endangered species and landscapes, assessing species extinction risk (Fordham et al., 2012; Omar and Elgamal, 2021), and understanding phylogeographic patterns (Guillera-Arroita et al., 2015).

The estimated model can help to choose the areas where the unknown populations of species can be located. According to our results, the most suitable areas are in the mountainous part of east Mazandaran. However, during LGM optimal conditions were in the more western areas, therefore it is possible that in some small mountainous refugia, this species thrived during the climatic fluctuations. In the case of such a rare species, finding even a single new population can be of great conservation importance.

From previous results on the genus *Acer* (Taleshi et al., 2019) and this study, the future of the genus *Acer* in the Hyrcanian forest is worrisome based on the predictive models. This is far more worrying for *A. mazandaranicum* for three reasons: 1) a few populations remain; 2) there is a low frequency of trees within the populations; and 3) little information is available for this species, especially for forest managers, due to its recent discovery (Amini et al., 2008). This recently discovered tree species represents a novel taxonomic entity, and even proficient researchers currently possess limited understanding of this taxon. Designated as an endangered tree species by the IUCN, this taxa was first documented and introduced to the scientific community in 2008. Therefore, to ensure the persistence of this plant over a prolonged period it is necessary to prioritize ex situ conservation of the few remaining populations. Additionally, exploring the genetic diversity and population structure of this species in the Hyrcanian forest should be considered another important research priority. This will be a remarkable assist in obtaining more reliable information that can be used to implement effective protection and management measures aimed at reducing the risks faced by this endangered species and preventing its extinction.

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CRediT authorship contribution statement

Walas Łukasz: Writing – review & editing, Writing – original draft, Formal analysis. **Yousefzadeh Hamed:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Data curation, Conceptualization. **Song Yi-Gang:** Methodology. **Pouramin Mansour:** Investigation, Conceptualization. **Alipour Shirin:** Writing – original draft, Data curation. **Amirchakhmaghi Narjes:** Writing – original draft, Conceptualization. **Kozlowski Gregor:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2023.121654.

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