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Original Scientific Paper

Modelling the distribution of the Caucasian oak (*Quercus macranthera*) in Western Asia under future climate change scenarios

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ABSTRACT:
The Caucasian oak (*Quercus macranthera*), a native tree of Western Asia, typically grows at high altitudes where the effects of climate change are particularly notable. We analysed the climatic determinants of the current distribution of *Q. macranthera* and assessed the redistribution of areas suitable for this species as a consequence of climate change. We described the current range of distribution and predicted the potential geographical distribution of the Caucasian oak using species distribution models and five algorithms from two Shared Socio-Economic Pathways (SSPs: SSP 1-2.6 and 5-8.5) for the years 2035, 2055, and 2085, which are based on two General Circulation Models (GCMs). The Random Forest algorithm most accurately described the current distribution of *Q. macranthera*. SSP 1-2.6 and SSP5-8.5 predicted a pronounced contraction of the highly suitable habitat for the Caucasian oak due to the increase in temperatures and changes in seasonal precipitation dynamics, that more intensive climate change could lead to a greater loss of highly suitable habitats, and that the populations of *Q. macranthera* could survive only in the Alborz Mountains (northern Iran) and in the Great Caucasus Mountains. Our work helps to establish conservation strategies for species monitoring in order to minimise the potential impacts of climate change.

Keywords:
CMIP6, global warming, potentially suitable habitat, random forest, species distribution models

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INTRODUCTION

The average global temperature is estimated to be at least 1.5°C higher by the end of the century (Allen *et al.* 2018), and this increase is expected to affect plant distributions in complex ways (Araújo *et al.* 2005; Carter & Prince 2019) both at regional and global levels (Reyer *et al.* 2013; Huang *et al.* 2021). These effects could be seen differently at different spatial scales and with different plant species due to their existing adaptations to habitats (Thuiller *et al.* 2005). Most trees are highly sensitive to temperature and their ranges may shrink considerably or their treelines shift towards cooler areas in response to rising temperatures (Sykes *et al.* 1996; Iverson & Prasad 1998; Buras & Menzel 2019), while some species might increase their distribution range (Vacchiano & Motta 2015; Dyderski *et al.* 2018).

The most extensive forest areas in Western Asia are found in Georgia, Iran, and Turkey, where mountain barriers trap the humidity from moist air masses and cause abundant rains; these luxuriant temperate broadleaf and mixed forests are often referred to as temperate rainforests (Nakhutsrishvili *et al.* 2015; Parolly 2020). Geographically, they are divided into two sub-provinces: the Euxine-Colchic broadleaf forests of Turkey and Georgia and the Caspian Hyrcanian forests of northern Iran (Browicz 1989; Nakhutsrishvili *et al.* 2015). There are several different oak species growing in these forests: *Quercus castaneifolia* C.A. Mey., *Quercus pontica* K. Koch, *Quercus hartwissiana* Steven, *Quercus macranthera* Fisch. & C.A. Mey. ex Hohen, and *Quercus petraea* (Matt.) Liebl. (Nakhutsrishvili *et al.* 2015; Parolly 2020). *Quercus macranthera* Fisch. & C.A.Mey. ex Hohen grows at altitudes above 1000 m in Anatolia and reaches 2500 m a.s.l. in Iran (Davis 1982; Sharafieh & Sagheb-Talebi 2012). The bioclimatic tolerance of this oak is wide and ranges from semiarid-freezing to perhumid-temperate conditions (Kargioglu *et al.* 2011). There are two subspecies of the Caucasian oak, the endemic *Q. macranthera* subsp. *syspirensis* (C. Koch) Menitsky growing in thermophilic lower montane communities in the north and mid-montane shrub communities in the east of Anatolia (Davis 1982), and *Quercus macranthera* subsp. *macranthera* Fisch. & Mey. ex Hohen. found in the subalpine deciduous forests of Iran and the South Caucasus (Akhani *et al.* 2010).

Oak species often dominate deciduous forests in Western Asia where they may serve as foundation species (Greller 2013; Bargali *et al.* 2015; Nakhutsrishvili *et al.* 2015). Our knowledge about climate change impacts on the distribution and diversity of oaks or other important tree species of the temperate forests in the West Asia region is limited (Akatov 2009; Gigauri *et al.* 2013; Taleshi *et al.* 2019; Valavi *et al.* 2019; Dagtekin *et al.* 2020; Varol *et al.* 2021). The distribution of some oak species is predicted to shrink in central and south-western Europe, China, Anatolia, and Levant (Czúcz *et al.* 2011; Al-Qaddi *et al.* 2017; López-Tirado *et al.* 2018; Çoban *et al.* 2020; Sun *et al.* 2020). However, some oaks such as *Q. petraea* (Matt.) Liebl. and *Q. pubescens* Willd. are expected to expand their distribution range from the Mediterranean to Central Europe (Zimmermann *et al.* 2013; Buras & Menzel 2019).

Quercus macranthera shows a limited latitudinal distribution occurring in Anatolia, the Caucasus, and northern Iran, and its bioclimatic range is variable. In different habitats this species might respond differently to future climate change (Czúcz *et al.* 2011; Zimmermann *et al.* 2013). Accordingly, we raised the following question: how might this oak species change its distribution range under various climate scenarios across the Anatolian-Caucasian-Iranian mountainous areas where global warming is already strongly manifested? In search for answers, we analysed the current climatic envelope of the geographical distribution of the Caucasian oak which spreads below the treeline ecotone in the Caucasus-Anatolian-Hyrcanian temperate forests; we used species distribution models (SDMs), and assessed the potential alterations of climatically suitable areas for this species caused by future climate change (Pearson 2007; Elith & Leathwick 2009).

Our specific aim was to determine the current distribution of the Caucasian oak and coherently predict its future distribution range under various climate scenarios with the best-performing model. This can help to outline conservation strategies to prevent or mitigate the adverse effects of climate change on the Caucasian oak, and serve as an important resource for new effective forest management policies.

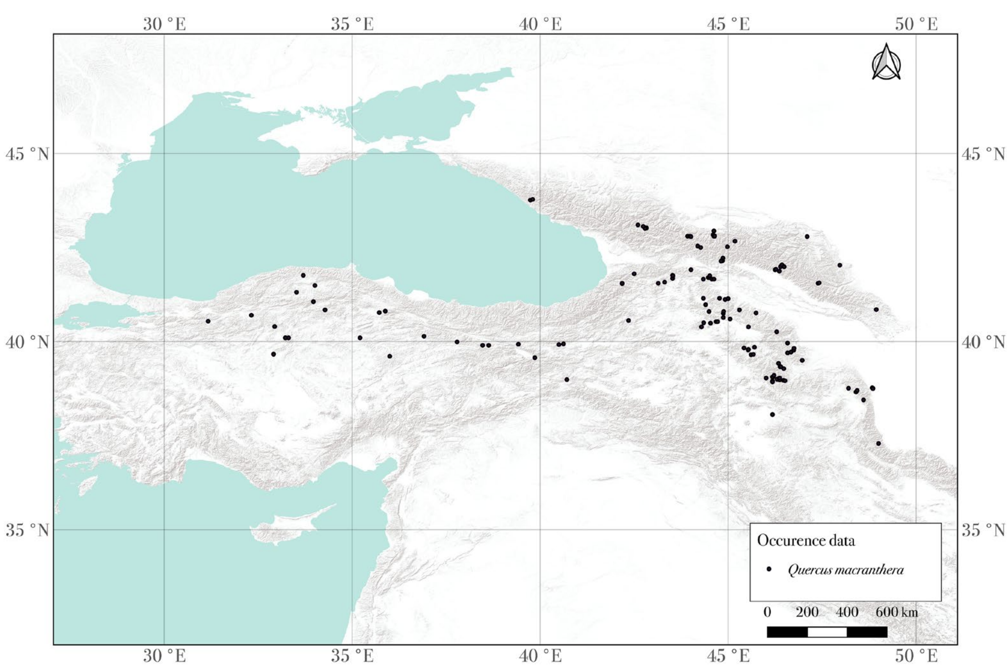

Fig. 1. The map of the current geographical distribution of *Quercus macranthera* based on the occurrence points obtained in this study.

MATERIALS AND METHODS

The study area and data collection. The study region (N 45°–35°, E 30°–55°) encompasses the north of Anatolia, the South Caucasus, and the north of Iran. This region is the native range of *Quercus macranthera* located in the Euro-Siberian floristic region. We retrieved the occurrence data for *Q. macranthera* from GBIF (2022), plus fieldwork observations kindly provided by Dr Jana Ekhvaia, Dr Zezva Asanidze, and Dr Giorgi Mikeladze. These records were verified in the available literature (Quézel *et al.* 1980; Davis 1982; Ekhvaia *et al.* 2018) and corrected if they contained any incorrect spatial or duplicated points. We finally listed a total of 133 occurrence records of both subspecies for our analyses (Supplementary Table 1; Fig. 1).

We obtained 19 current bioclimatic variables (1981 to 2010) from CHELSA version 2.1 (Karger *et al.* 2021; Table 1) at a 30-arc-second spatial resolution (~1 km). The bioclimatic data were extracted using QGIS 3.18.2 (QGIS Development Team 2021) for each presence point, and added to the current distribution map. The CHELSA dataset offers global climate model (GCM) simulations for the future periods: 2011–2040 ("2035s"), 2041–2070 ("2055s"), and 2071–2100 ("2085s"). We used the variables from two future GCMs: Max Planck Institute Earth System Model (MPI-ESM1-2-HR; Gutjahr *et al.* 2019) and the Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2.0; Yukimoto *et al.* 2019).

Each model was run on two Shared Socio-Economic Pathways (SSPs) released as Coupled Model Intercomparison Project Phase 6 (CMIP6) and recently published in the Intergovernmental Panel on Climate Change's sixth assessment report (IPCC AR6; WGI 2021). The SSPs deal with "future socioeconomic changes" and "efforts to mitigate climate change" in addition to the existing concept of Representative Concentration Pathways (RCP; An *et al.* 2022). The SSP1-2.6 is an optimistic scenario envisaging a more sustainable, limited CO_2 emissions approach, staying below 2.0°C warming, and with a 2.6 W/m² radiative forcing level by the year 2100, whilst the SSP5-8.5 is a pessimistic scenario which projects a radiative forcing level of 8.5 W/m² by the year 2100 and is based on the rapid and unconstrained growth in economic output and energy consumption with the highest greenhouse gas emissions (Meinshausen *et al.* 2020).

Data analysis. We calculated the Variance Inflation Factors (VIF) of the climatic variables to avoid multicollinearity in the usdm R package v1.1-18 (Naimi *et al.* 2014). We removed the bioclimatic variables with VIF values higher than 5; the remaining six variables - bio1, bio3, bio4, bio8, bio15, and bio19 all showed relatively low correlation with the others ($|r| < 0.60$), and were consequently used in our models (Table 1).

Table 1. The set of climatic variables used to build the models retrieved from CHELSA Version 2.1 (Karger *et al.* 2021) and their Variance Inflation Factor (VIF) values used to build the models.

Code	Bioclimatic Variable	VIF value
BIO1	Annual Mean Temperature	2.91
BIO3	Isothermality (BIO2/BIO7) (* 100)	1.89
BIO4	Temperature Seasonality (standard deviation *100)	1.89
BIO8	Mean Temperature of Wettest Quarter	4.20
BIO15	Precipitation Seasonality (Coefficient of Variation)	1.53
BIO19	Precipitation of Coldest Quarter	3.21

Species distribution models (SDMs) describe species distributions based on the correlations between the known occurrence records and the environmental conditions at present localities (Beery *et al.* 2021). We also used the R package biomod2 version 3.5.1 as a computer platform for SDMs (Thuiller *et al.* 2021). This package allowed for the calculation of the mean values and the significance of six environmental variables (expressed as percentage shares). We used the Generalised Linear Model (GLM), the General Additive Model (GAM), and Random Forest (RF) algorithms which work with presence-absence data, along with Surface Range Envelope (SRE/BIOCLIM) and Maximum Entropy (MaxEnt) algorithms which use presence-only data and pseudo-absence (background) data in the modelling process (Thuiller *et al.* 2009; Elith & Franklin 2013). We generated 1000 random pseudo-absence records (PAs) under the default setting for data formatting and used 80% and 20% of the input data as a training sample and a test sample, respectively. We repeated the modelling process three times, resulting in 180 models in total (3 folds × 5 algorithms × 2 GCMs × 2 future scenarios × 3 time periods). The accuracy of the models was measured by the Area Under the ROC Curve (AUC) and True Skills Statistics (TSS). The AUC value ranges between 0 to 1, where a value of 0 represents a perfectly inaccurate result and a value of 1 reflects a perfectly accurate result (Mandrekar 2010). TSS = sensitivity + specificity - 1; the greater the three values are, the higher the accuracy of the model is (Allouche *et al.* 2006).

We quantified the habitat suitability of the maps ranging from 0 to 1 based on the best fit model (Random Forest) results obtained from biomod2. For visualisation and further analysis, we imported the biomod2 forecasting results into QGIS 3.18.2, and produced maps with five levels of suitability: unsuitability (0–0.2), low suitability (0.2–0.4), medium suitability (0.4–0.6), suitability (0.6–0.8), and high suitability (0.8–1).

RESULTS

Model performance. The models provided valid estimates of performance. The AUC values varied from 0.826 to 0.955 and the mean of TSS ranged from 0.654 to 0.848 (Table 2). Random Forest (RF) appeared to be the most stable model with the highest degree of accuracy (AUC = 0.955, TSS = 0.848), while the least accurate was BIOCLIM (AUC = 0.826, TSS = 0.654). Therefore, we considered the RF model to be the most accurate algorithm for predicting the distribution of *Q. macranthera* under future climate scenarios.

The importance of the environmental variables. In all the tested models the output was most dependent on the variation of the annual mean temperature (bio1) and precipitation seasonality (bio15) (Fig. 2). The relative importance of temperature seasonality (bio4) was notable in GLM, BIOCLIM, and MaxEnt. However, annual mean temperature (bio1) was the most important variable in all the tested models.

Potentially suitable habitat under current and future climate conditions. The exact occurrence points of *Q. macranthera* (Fig. 1) all fell within the area predicted by the RF model. The potential future projections based on two GCMs predicted a severe range contraction of the distribution of the Caucasian oak by 2100, although SSP1-2.6 produced a rather less dramatic change (Figs. 3-5).

The extents of the current and future potential distribution areas are shown in Table 3. The highly suitable areas for *Q. macranthera* currently cover 194,641 km^2; however, even under the optimistic scenario of a sustainable world (SSP1-2.6) the species distribution is already expected to have contracted considerably by 2040, and then to continue contracting further as shown by the 2085 projections (Table 3). For example, highly suitable areas were predicted to radically decrease by 4 to 10 times. Under the MPI-ESM1-2-HR GCM, the optimistic scenario SSP1-2.6 predicted stabilisation after losses of 75% of the species' current distribution range by end of the century, even followed by some minor gains within this period. Under the pessimistic scenario SSP5-8.5, *Q. macranthera* is certainly expected to lose considerably more ground: from the current range of 194,641 km^2 to 68,317 km^2, which means that only 35% of the highly suitable area might remain as early as 2035. After this, the habitat contraction was predicted to continue: the Caucasian oak might lose 74% and 89% of its highly suitable habitats by 2055 and 2085, respectively. The MRI-ESM2.0 GCM predicted an even more dramatic decrease in highly suitable area from the current range of 194,641 km^2 to 42,446 km^2 (78% loss) by 2035, and a further contraction to 15,317 km^2 (92% loss) by the end of the century. Thus, in the worst-case scenario, this oak species might lose 92% of its highly suitable habitat by the end of the century.

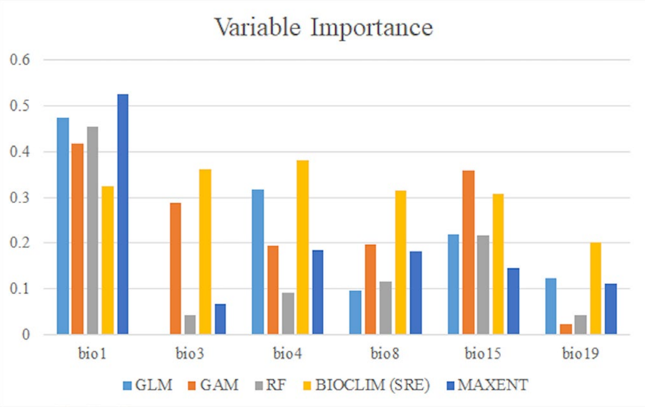

Fig. 2. The relative importance of the environmental variables to the GLM, GAM, RF, BIOCLIM (SRE) and MaxEnt models.

Table 2. The AUC and TSS values (± SD) of all the algorithms, random forest (RF), generalised linear model (GLM), generalised additive model (GAM), BIOCLIM, and maximum entropy (MaxEnt) performed with the present climate conditions (1981–2010).

	AUC	TSS
RF	0.955 ± 0.087	0.848 ± 0.030
GLM	0.936 ± 0.023	0.796 ± 0.056
GAM	0.902 ± 0.040	0.780 ± 0.046
BIOCLIM	0.826 ± 0.020	0.654 ± 0.040
MaxEnt	0.903 ± 0.014	0.739 ± 0.054

DISCUSSION

Quercus macranthera is a subalpine tree species in the triangle of the Caucasus, Turkey, and north-east Iran. This region is located at the intersection of the Euro-Siberian and Irano-Turanian phytogeographical regions. Thus, this oak species occurs in the Euxine-Colchic deciduous forests of Georgia and Turkey, as well as in the Hyrcanian mixed forests of Iran (Davis 1982; Nakhutsrishvili *et al.* 2015). It also coexists with *Pinus nigra* J.F. Arnold, *Pinus sylvestris* L., *Quercus pubescens* Willd., *Quercus petraea* (Matt.) Liebl., and *Populus tremula* L. in semi-arid habitats of Anatolia (Kayacik 1981; Yaltirik 1984). The Caucasian oak generally occurs above the *Fagus orientalis* Lipsky belt and forms pure stands, or mixes with *Betula litwinovii* Doluch., *Carpinus caucasica* Grossh., *Acer hyrcanum* Fisch. & C.A.Mey., and *Fraxinus excelsior* L. in temperate deciduous forests (Zohary 1973; Nakhutsrishvili 1999; Papini *et al.* 2011). The Caucasian oak grows at altitudes above 1000 m, and can even reach up to 2500 m a.s.l., probably profiting from local climate peculiarities (Kargioglu *et al.* 2011).

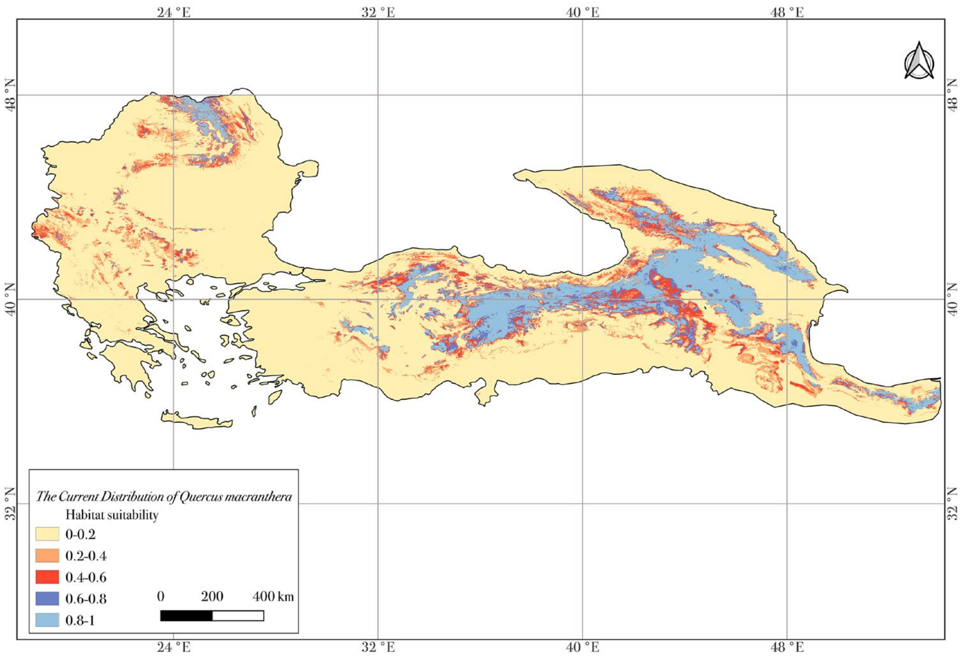

Fig. 3. The current (1981-2010) suitable habitats for *Quercus macranthera* predicted based on the Random Forest algorithm. Yellow (0-0.2) represents unsuitability, orange (0.2-0.4) represents low suitability, red (0.4-0.6) represents medium suitability, dark blue (0.6-0.8) represents suitability, and light blue (0.8-1) represents high suitability.

Table 3. The percentage and predicted geographical distribution range for the presence of *Quercus macranthera* for the present day (1981-2010), and future climates (2035s, 2055s, 2085s) under two GCMs [MPI-ESM1-2-HR and MRI-ESM2-0] and two Shared Socio-Economic Pathways [SSP1-2.6 and SSP5-8.5]. Suitability class code: unsuitability (0-0.2), low suitability (0.2-0.4), medium suitability (0.4-0.6), suitability (0.6-0.8), and high suitability (0.8-1).

Random Forest	MPI-ESM1-2-HR													
Suitability Class Code	**Current**		**2035-SSP126**		**2055-SSP126**		**2085-SSP126**		**2035-SSP585**		**2055-SSP585**		**2085-SSP585**	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
0-0.2	1.432,9	73.33	1.658,6	84.88	1.654,7	84.68	1.687,8	86.37	1.632,3	83.53	1.705,7	87.29	1.806,0	92.42
02-0.4	163.819	8.38	129.661	6.64	118.768	6.08	112.235	5.74	133.837	6.85	103.982	5.32	67.784	3.47
0.4-0.6	93.399	4.78	56.149	2.87	57.502	2.94	46.672	2.39	56.640	2.90	46.798	2.39	31.239	1.60
0.6-0.8	69.362	3.55	61.790	3.16	65.047	3.33	58.989	3.02	63.036	3.23	47.109	2.41	27.856	1.43
0.8-1	194.641	9.96	47.899	2.45	58.132	2.97	48.409	2.48	68.317	3.50	50.512	2.58	21.211	1.09
Total	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100
	MRI-ESM2-0													
Suitability Class Code	**Current**		**2035-SSP126**		**2055-SSP126**		**2085-SSP126**		**2035-SSP585**		**2055-SSP585**		**2085-SSP585**	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
0-0.2	1.432,9	73.33	1.682,0	86.07	1.687,0	86.33	1.677,3	85.84	1.686,4	86.30	1.739,1	89.0	1.801,5	92.19
02-0.4	163.819	8.38	106.808	5.47	105.296	5.39	116.430	5.96	112.888	5.78	102.258	5.23	81.942	4.19
0.4-0.6	93.399	4.78	53.390	2.73	52.775	2.70	56.539	2.89	58.175	2.98	40.407	2.07	31.414	1.61
0.6-0.8	69.362	3.55	57.752	2.96	51.762	2.65	54.757	2.80	54.205	2.77	36.081	1.85	23.963	1.23
0.8-1	194.641	9.96	54.171	2.77	57.221	2.93	49.062	2.51	42.446	2.17	36.213	1.85	15.317	0.78
Total	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100	1.954,1	100

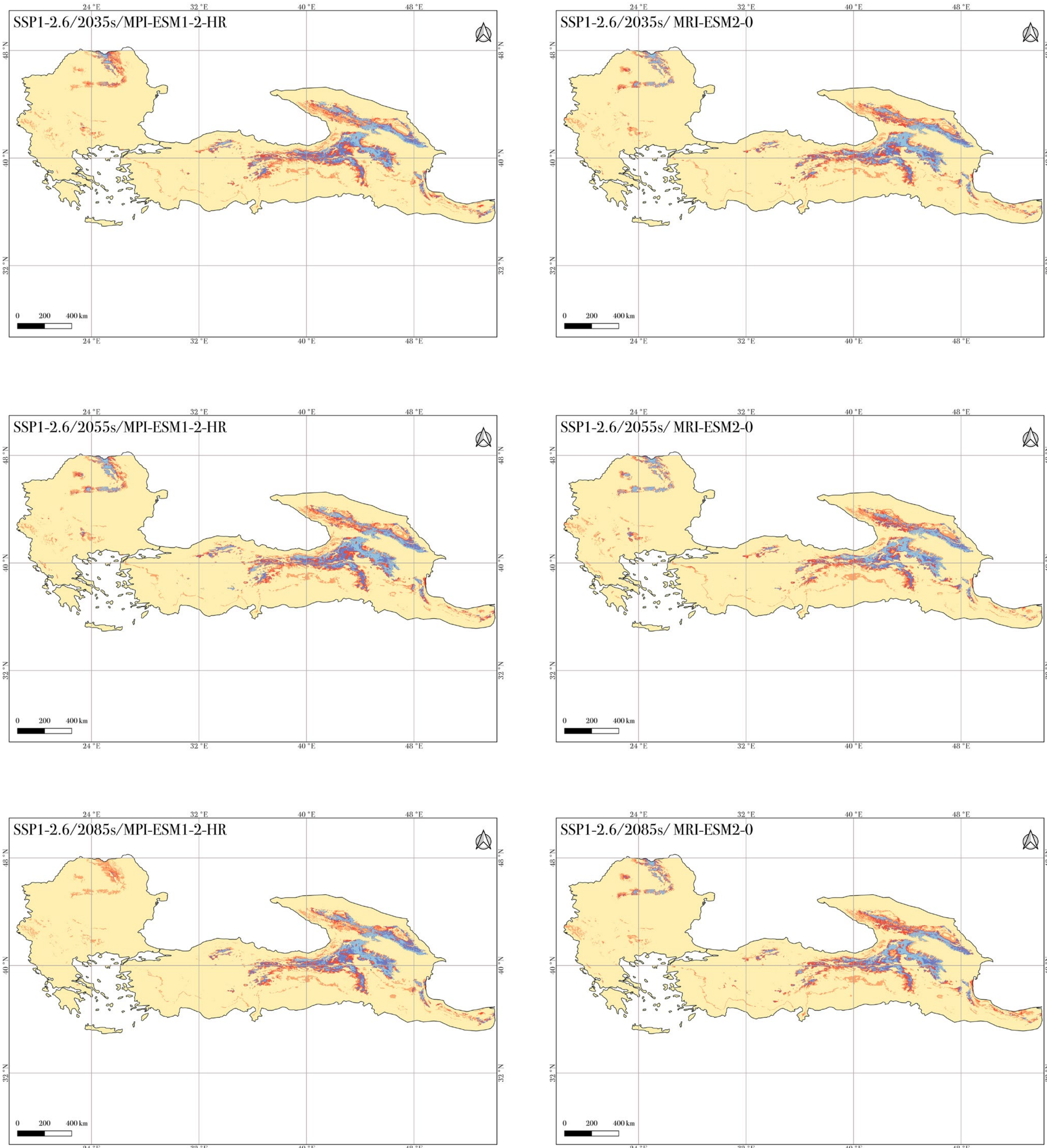

Fig. 4. The spatial distributions of potential suitable habitats of *Quercus macranthera* under the SSP1-2.6 scenario in 2035s, 2055s, and 2085s, respectively, according to the MPI-ESM1-2-HR and MRI-ESM2-0 GCMs based on the Random Forest algorithm. Yellow (0–0.2) represents unsuitability, orange (0.2–0.4) represents low suitability, red (0.4–0.6) represents medium suitability, dark blue (0.6–0.8) represents suitability, and light blue (0.8–1) represents high suitability.

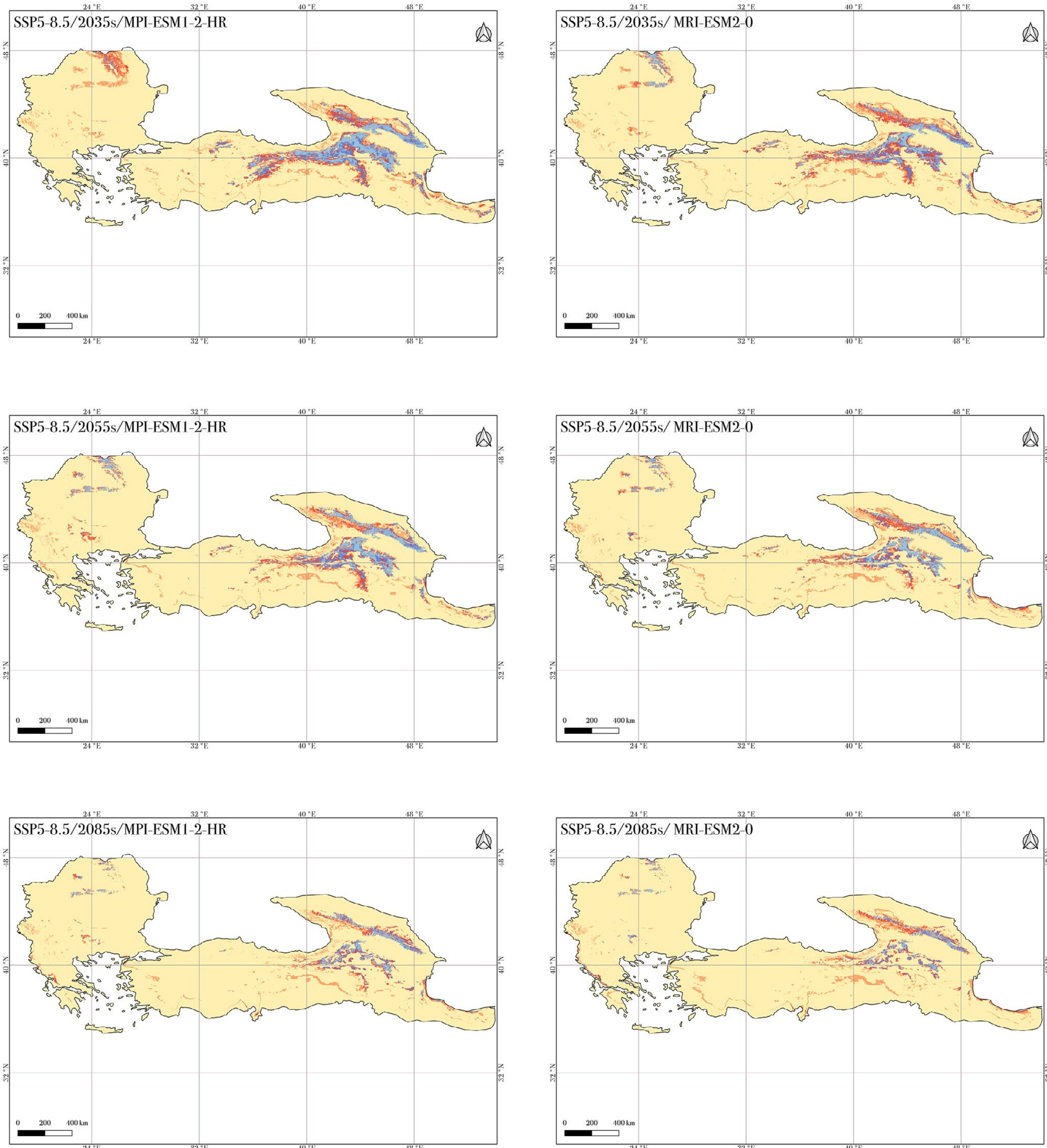

Fig. 5. The spatial distributions of potential suitable habitats of *Quercus macranthera* under the SSP5-8.5 scenario in 2035s, 2055s, and 2085s, respectively, according to the MPI-ESM1-2-HR and MRI-ESM2-0 GCMs based on the Random Forest algorithm. Yellow (0–0.2) represents unsuitability, orange (0.2–0.4) represents low suitability, red (0.4–0.6) represents medium suitability, dark blue (0.6–0.8) represents suitability, and light blue (0.8–1) represents high suitability.

Generally, the geographical distribution of plants strongly depends on climate, but spatial constraints also affect these distributions (Blach-Overgaard *et al.* 2010). Temperature, precipitation seasonality, and annual or monthly temperature-precipitation extremes are important climatic drivers for alpine and subalpine habitats (Kerr 1975; Lisovski *et al.* 2017; Testolin *et al.* 2020). Still, regional climate prediction can be uncertain owing to the complexity of natural systems (Mitchell & Hulme 1999). The climate in the Middle Holocene was significantly warmer and drier than in Anatolia and southern Europe today (Strandberg *et al.* 2022). We also know that *Q. macranthera* had a wide range in subalpine forests (Janelidze & Margalitadze 1977; Margalitadze 1998), particularly on the slopes of the Central Great Caucasus in this period thanks to palaeobotanical evidence (Nakhutsrishvili *et al.* 2006). However, this knowledge does not help to predict the response of the Caucasian oak to global warming as the leading variable we have to deal with is temperature, with precipitation playing a lesser role. Our use of SDMs shows that these models can address this problem by combining multiple climatic variables. Indeed, the performed modelling suggests that the distribution range of the Caucasian oak is mainly linked to the annual mean temperature (bio1) and the precipitation seasonality (bio15). The optimum temperature range of *Q. macranthera* is between 6°C and 9°C and it is lower than that of other oak species such as *Q. aucheri* and *Q. petraea* (Zohary 1973; Kargioglu *et al.* 2011). Precipitation seasonality can be an important climatic variable since it is related to periodic droughts and changes in hydrologic balance, which affect oak growth and survival (Weltzin *et al.* 2001; Costa *et al.* 2002; di Filippo *et al.* 2010).

In our study, the Random Forest algorithm accurately and consistently delineated the distribution of *Q. macranthera* under the current climate conditions. The RF method provides successful results probably since it is based on the use of both classification and regression tree algorithms (Li & Wang 2013; Zhang *et al.* 2019). BIOCLIM always performs poorly in simulations compared to other modelling approaches because it is a less complex algorithm and underperforms in classification (Elith *et al.* 2006; Hijmans & Graham 2006).

Our study reveals the potential loss, contraction, or shift in the distribution range of *Q. macranthera* in the future under different climate change scenarios. The mildest impact on the potential distribution area of *Q. macranthera* was predicted under the optimistic scenario (SSP1–2.6) of climate change, which amounts to the loss of 3/4 of the currently highly suitable habitat where the plant can reproduce its population; a stabilisation was then expected after this loss. Under the pessimistic scenario (SSP5–8.5) of climate change the loss of 3/4 of the currently highly suitable area was expected to already occur before 2040, with a further decline by the end of the century: *Q. macranthera* could lose approximately 90% of its highly suitable habitats by 2100. Warmer and drier conditions, and variability in the precipitation regime seem to cause these losses (Zhang *et al.* 2021). Therefore, the models predicted that *Q. macranthera* populations might survive on the slopes of the Greater and Lesser Caucasus Mountains and the western Caspian coastal mountains thanks to the more favourable climate in the South Caucasus. Likewise, the future projections for *Fagus orientalis* forests occurring below *Q. macranthera* communities (Talebi *et al.* 2014) also indicated the Alborz Mountains in the south of the Caspian Sea and the Caucasus Mountains as the major potential future refugia for this beech (Dagtekin *et al.* 2020).

Representatives of the oak genus are found in a large variety of environments, yet individual species can have quite specific requirements for survival, whereby the oaks can differ greatly from each other (Dickson & Tomlinson 1996). For example, subalpine oaks in the Himalayas form climax forests and cannot easily regenerate after disturbance owing to the altered soils, water and temperature relations (Singh & Singh 1986). Similarly, the Caucasian oak is actually the major element of the old-growth Euxine-Colchic broadleaf and Caspian-Hyrcanian forests in spite of growing in semi-arid areas in Anatolia (Dolukhanov 1978; Akhani *et al.* 2010; Nakhutsrishvili 2012), and, as our results showed, in spite of relative climatic tolerance, *Q. macranthera* populations could be sensitive to climatic variability in the future. This species remained stable in its spatial distribution through the Quaternary Period (Talebi *et al.* 2014), seemingly thanks to the relatively stable climate of these refugial areas. However, our use of climate change predictions showed that the climatic envelope suitable for the Caucasian oak might contract considerably and threaten the existence of this species. This threat may also lead to the extinction of other characteristic species of the climax oak communities, or bring a notable decline in their function and structure. Climax communities are known to provide ecosystem services and diverse forest resources (Haines-Young & Potschin 2010), so the loss of the Caucasian oak habitats may mean the loss of these services and resources such as soils (Talebi *et al.* 2014). Due to the decline in the forest cover and changes in their community structure, human well-being reliant on these forests may also be severely affected (McMichael *et al.* 2005).

Generally, climate change is expected to lead to the range contractions or distribution shifts of plant species (Thuiller 2007; Thomas 2010; Dullinger *et al.* 2012; Dubos *et al.* 2022). In the mountains, the “escalator to extinction” mechanism threatens the existence of many species adapted to high altitudes: warmer temperatures can force plants to shift their ranges to the upper slopes, but in many locations this shift can reach summits where cool-adapted species cannot shift further up and thus become locally extinct (Parolo & Rossi 2008; Akatov 2009). Furthermore, because of the roughly conical shape of mountains, the area of a given habitat becomes smaller with the increasing altitude and this might exacerbate the threat of extinction of the species associated with this habitat (Bisht & Kuniyal 2013; Freeman *et al.* 2018). The fate of *Q. macranthera* might be exacerbated by the fact that, generally, oak species are competitively inferior to neighbouring trees, mainly beech species (Otto *et al.* 2009; Ligot *et al.* 2013); therefore, beech can easily encroach *Q. macranthera* stands to supplant oak at its lower distribution limits.

CONCLUSION

Today, *Q. macranthera* occurs in the north of Turkey in the Pontic Mountains, the Caucasus mountains, and the Alborz Mountains in northern Iran. The future projections from our study predict that, due to the rise of temperatures and differentiation in seasonal precipitation dynamics, *Q. macranthera* populations might only survive in the Alborz Mountains close to the Caspian Sea and the Greater and Lesser Caucasus Mountains. Our study also shows how climate change can affect *Q. macranthera,* a typical subalpine tree species, without any direct human impact such as land use, deforestation, or grazing. It also provides insight into the effective choice of future suitable areas for nature conservation and effective restoration measures.

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REZIME

Botanica SERBICA

Modeliranje distribucije kavkaskog hrasta (*Quercus macranthera*) u zapadnoj Aziji prema budućim scenarijima klimatskih promena

Nihal Kenar i Zaal Kikvidze

Kavkaski hrast (*Quercus macranthera*), autohtono drvo zapadne Azije, obično raste na velikim visinama gde su efekti klimatskih promena posebno primetni. Analizirali smo klimatske determinante sadašnjeg rasprostranjenja *Q. macranthera* i procenili preraspodelu površina pogodnih za ovu vrstu kao posledicu klimatskih promena. Opisali smo trenutni opseg distribucije i predvideli potencijalnu geografsku distribuciju kavkaskog hrasta koristeći modele distribucije vrsta i pet algoritama iz dva zajednička socio-ekonomska puta (SSP: SSP 1–2.6 i 5–8.5) za godine 2035, 2055. i 2085. koji su zasnovani na dva Opšta modela cirkulacije (GCMs). TAlgoritam Random Forest je najtačnije opisao trenutnu distribuciju *Q. macranthera*. SSP 1–2.6 i SSP5–8.5 predviđaju veliku kontrakciju veoma pogodnog staništa za kavkaski hrast usled porasta temperatura i promena u dinamici sezonskih padavina, da bi intenzivnije klimatske promene mogle dovesti do većeg gubitka veoma pogodnih staništa, i da su populacije *Q. macranthera* mogle da opstanu samo u planinama Alborz (severni Iran) i na Velikom Kavkazu. Ova studija pomaže u uspostavljanju strategija očuvanja za praćenje vrsta kako bi se minimizirali potencijalni uticaji klimatskih promena.

Ključne reči: CMIP6, globalno zagrevanje, potencijalno pogodno stanište, slučajna šuma, modeli distribucije vrsta