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MODELING THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON THE DISTRIBUTION OF TETRATAENIUM LASIOPETALUM (APIACEAE) IN CHAHARMAHAL AND BAKHTIARI PROVINCE, IRAN

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Medicinal plants are crucial sources of bioactive compounds and serve as essential medicines for many people worldwide. Many species quickly disappear despite their growing popularity, and climate change worsens this issue. This study used the MaxEnt model to predict the impact of climate change on the distribution of *Tetrataenium lasiopetalum* in Chaharmahal and Bakhtiari province. The CCSM4 general circulation model and two climate scenarios, RCP2.6 and RCP8.5, for the 2050s and 2070s, were applied to predict the potential effects of climate on the species' distribution. According to the research findings, the model performed excellently in terms of prediction accuracy (AUC $\geq$ 0.9). The key environmental variables affecting species distribution were pH (59/1%), soil organic carbon (10/4%), slope (5/8%), sand (4/4%), altitude (4%), and precipitation of wettest month (Bio13) (4%). The MaxEnt model predicts that fewer than ten percent of potential suitable habitats of this species are located within environmental protection areas. The projected distribution of the species is expected to increase in the 2050s and decrease in the 2070s due to climate change. This study is the first to use a species distribution modeling approach to predict suitable habitats for *T. lasiopetalum*. The results offer valuable insights into the protection, management, and future research efforts needed to preserve this valuable species in Chaharmahal and Bakhtiari province.

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Keywords: Apiaceae; conservation; global warming; medicinal plants; migration; species distribution modeling

مدل‌سازی اثرات بالقوه تغییر اقلیم بر پراکنش Tetrataenium lasiopetalum در استان چهارمحال و بختیاری

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گیاهان دارویی منابع بسیار مهمی از ترکیبات فعال زیستی هستند و به عنوان داروهای ضروری برای بسیاری از مردم در سراسر جهان عمل می‌کنند. بسیاری از گونه‌ها علیرغم محبوبیت فزاینده خود به سرعت در حال ناپدید شدن هستند و تغییرات آب و هوایی این موضوع را بدتر می‌کند. در این مطالعه از مدل MaxEnt برای پیش‌بینی تأثیر تغییر اقلیم بر پراکنش Tetrataenium lasiopetalum در استان چهارمحال و بختیاری استفاده شد. مدل گردش عمومی CCSM4 و دو سناریوی اقلیمی RCP2.6 و RCP8.5 در دهه‌های ۲۰۵۰ و ۲۰۷۰ برای پیش‌بینی اثر بالقوه اقلیم بر پراکنش

گونه موردمطالعه مورداستفاده قرار گرفت. بر اساس یافته‌های این پژوهش، عملکرد مدل برای پیش‌بینی عالی (AUC≥0.9) بوده است. متغیرهای محیطی کلیدی مؤثر بر پراکنش گونه عبارتند از اسیدیته (۵۹/۱٪)، کربن آلی خاک (۱۰/۴٪)، شیب (۵/۸٪)، درصد شن (۴/۴٪)، ارتفاع (۴٪) و بارش در مرطوب‌ترین ماه (Bio13) (۴٪). مدل MaxEnt پیش‌بینی می‌کند که کمتر از ده درصد از زیستگاه‌های مناسب بالقوه این گونه در مناطق حفاظت شده سازمان محیط زیست قرار دارند. انتظار می‌رود پراکنش پیش‌بینی شده این گونه در دهه ۲۰۵۰ افزایش یابد و در دهه ۲۰۷۰ به دلیل تغییرات آب و هوایی کاهش یابد. این مطالعه نخستین مطالعه‌ای است که از یک رویکرد مدل سازی پراکنش گونه‌ای برای پیش‌بینی زیستگاه‌های مناسب برای T. lasiopetalum استفاده می‌کند. نتایج به دست آمده اطلاعات ارزشمندی را برای حفاظت، مدیریت و تحقیقات بیشتر این گونه گیاهی ارزشمند در استان چهارمحال و بختیاری ارائه می‌دهد.

INTRODUCTION

The impact of climate change on the planet's ecosystems is increasingly recognized as a serious threat to all forms of life (Grimm & al. 2013; Makki & al. 2023a). This includes significant disturbances in ecosystem structure and function. Climate change has various impacts on ecosystems, such as changes in species distribution, phenology, population reduction, and extinction (Sarkar & al. 2024). Plant species' growth and distribution depend on climate, topography, and soil characteristics. As climatic conditions change, the potential distribution of plant species also changes, leading to the disappearance or migration of sensitive species to new areas. Some species may adapt to these changes, while others may not (Hosseini & al. 2022). Therefore, understanding how climate change affects species distribution is crucial, especially for endangered medicinal plant species. This understanding is essential for informing researchers and scientists to make conservation decisions in response to future crises (Rana & al. 2017). The effective management and conservation of biodiversity must understand how species react to climate change and distribute under future climate change scenarios.

Various innovative methods have been used to study the geographical ranges of species under different climate change scenarios (Phillips & al. 2004; Rodríguez & al. 2007; Thuiller 2003; Makki & al. 2021, 2023b; Darabi & al. 2024; Khajoei Nasab & al. 2024a). These scenarios illustrate potential future climates based on anticipated levels of greenhouse gas emissions in the coming years (IPCC 2014). Representative Concentration Pathways (RCPs) are used to explore plausible options while accounting for uncertainties in future developments (IPCC 2014). According to the Intergovernmental Panel on Climate Change (IPCC), RCP 2.6 requires that carbon dioxide (CO_2) emissions start to decline by 2020 and reach zero by 2100 (IPCC 2014). The goal of RCP 2.6 is to limit the global temperature rise to below 2 °C by 2100. In contrast, RCP 8.5 presents a more pessimistic scenario, where emissions continue to rise throughout the 21st century, reaching 940 ppm by 2100 and continue increasing for another 100 years (IPCC 2014). One widely used method is species distribution models (SDMs), which can estimate current and future species distribution. The maximum entropy model (MaxEnt) is a specific SDM commonly used to assess species' ecological needs, environmental responses, and habitat suitability (Momeni Damaneh & al. 2022; Khajoei Nasab & al. 2022). This model has demonstrated superior performance in handling limited sample size and presence data compared to other models (Ahmadi & al. 2023; Khajoei Nasab & al. 2024b).

Medicinal and aromatic plants, like all living members of the biosphere, are vulnerable to the effects of climate change. These plants are crucial in conventional medical systems and are considered economically important. Therefore, the impact of climate change on these plants could have devastating consequences on society (El Gendy & al. 2023). The important effects of climate change on medicinal plants include changes in distribution, product performance, and the production system (Aryal 2015; Cavaliere 2009). According to recent findings, 25.93% of plant species in Iran are used in traditional medicine, many of which are endemic to Iran or have a limited distribution (Mozaffarian 2013). The Chaharmahal and Bakhtiari province boasts a rich flora due to its special climatic conditions and topography, with approximately 28.75% of its flora being valuable medicinal plants (Mozaffarian 2013). The flora of this province contains several valuable medicinal species, some of which are exclusive to Chaharmahal and Bakhtiari province or are at significant risk of extinction. However, there have been limited studies conducted on their distribution and the impact of climate change on these species (Zeraatkar & al. 2023). In the field of species distribution modeling, Haidarian Aghakhani & al. (2017) conducted a study on how climate change affects the potential distribution of *Prunus scoparia* (Spach) C.K.Schneid. in Chaharmahal and Bakhtiari province. The studies by Naghipour Borj & al. (2019b) and Teimoori Asl & al. (2020) modeled the impact of climate change on the potential habitat of *Fritillaria imperialis* L. and *Stipa hohenackeriana* Trin & Rupr. They predicted that the favorable habitats of these species would change in response to climate change. Studies show the distribution of certain species such as *Astragalus adscendens* (Haidarian & al. 2021), *Salvia hydrangea* DC. ex Benth. (Ghehsareh Ardestani & Heidari Ghahfarrokhi 2021), *Crataegus azarolus* L. (Naghipour & al. 2021a), *Juniperus excelsa* M. Bieb (Naghipour & al. 2021b), *Prangos ferulacea* (L.) Lindl (Babaei & al. 2022), and *Hordeum bulbosum* L. (Hosseini & al. 2022) would likely be significantly affected by climate change in the future in this province.

Tetrataenium lasiopetalum (Boiss.) Manden., locally known as *Karsum*, *Karson*, *Karso*, or *Kaleh* belongs to the Apiaceae family and is found in southwestern Turkey, the Zagros region of Iraq, and western and southwestern Iran (Rechinger 1987). Across the distribution range of the species, the lowest elevation habitat (1500-2500 meters above sea level) is associated with scattered juniper (*Juniperus excelsa* M.Bieb.) woodlands, where populations are sparse and fragmented. In contrast, the species is predominantly found in the subalpine and alpine zones of the Zagros Mountains, at elevations ranging from 2800 to 4000 meters above sea level, where large populations can occasionally be observed. The primary habitat of this species is located in Chaharmahal and Bakhtiari province, specifically in major mountain ranges such as Zardkuh, Kūh-e Mīlī, Kūh-e Garreh, Kūh-e Mafaron, Kūh-e Kallar, and Kūh-e Rīg. Furthermore, the species exhibits significant distribution across the high-altitude mountains of the Zagros range in adjacent provinces, including Lorestan and Isfahan provinces. Notable examples include Oshtorankuh, Kuh-e Garin, Ghali Kuh, Shahankuh, and the high-altitude areas of the Poshtkuh forest region, shared among these three provinces. These vast mountainous regions are characterized by numerous subalpine and alpine peaks, providing ideal conditions for the species' growth and expansion.

In traditional Iranian medicine, the leaves and fruits of *Tetrataenium lasiopetalum* are used as disinfectants and strong germicides (Sonboli & al. 2007). Studies have shown that *T. lasiopetalum* can remove toxins from the body, increase appetite, boost milk secretion, induce sweating due to its numerous hormones, antiflatulent, treat gastrointestinal disorders, and respiratory disorders (Sedaghat Boroujeni & al. 2013; Mehrnia & Hosseini 2023). The essential oil of *T. lasiopetalum* fruit also possesses antibacterial properties. Additionally, *T. lasiopetalum* is aromatic and is used as a spice (Ghasemi Pirbalouti & al. 2012; Mehrnia & Hosseini 2023). Extensive medicinal and edible uses of this plant have led to excessive harvesting.

Chaharmahal and Bakhtiari province is a significant area for the growth and distribution of this plant in Iran, with nearly half of its identified habitats located there (Mozaffarian 2007). Other habitats of *T. lasiopetalum* in Iran are in Hamadan, Kohgiluyeh and Boyer-Ahmad, Kermanshah, Isfahan, Lorestan, and Khuzestan provinces. The plant's type specimen was first collected in 1837 from ZardKuh by Pierre Martin Rémi Aucher-Éloy, a renowned French botanist and pharmacologist (Rechinger 1987). Over the past three years, our research team has conducted extensive studies revealing that this plant species is overharvesting in natural habitats. Despite its significance, there have been no studies on the conservation priorities of this species in the province. The environmental factors affecting its distribution are largely unknown. Therefore, we aim to conduct species distribution modeling studies to protect this plant species and propose management plans. This study aims to support the United Nations Sustainable Development Goals (SDGs) by identifying the potential distribution of valuable medicinal species and taking measures to protect and restore their habitats, thereby preventing biodiversity loss. This effort aligns with SDG 15, which focuses on life on land. Our research objectives are as follows: 1) to identify suitable habitats for the species under current climatic conditions, 2) to investigate the impact of climate change on its potential distribution in the 2050s and 2070s, and 3) to determine the key environmental variables that influence its distribution. The findings of this study could be instrumental in pinpointing potential habitats for cultivating it in natural areas and developing management strategies to protect it in Chaharmahal and Bakhtiari province.

MATERIALS AND METHODS

Study area

Chaharmahal and Bakhtiari province covers an area of approximately 16419 square kilometers in the western part of the country, nestled amidst the Zagros Mountains. The province is located between 31°9' to 32°48' N latitude and 49°30' to 51°26' E longitude. It is considered one of the mountainous regions of the central plateau of Iran. The altitude in the region ranges from 781 to 4178 meters, with an average elevation of about 2153 meters. The province experiences diverse climates and is categorized into 5 classes including humid, very humid A, very humid B, Mediterranean, and semi-humid (Tavousi & al 2021). The annual rainfall in the province is approximately 560 mm, with the highest amount of rainfall occurring in Kuhrang at around 1800 mm. The average annual air temperature ranges from 5 to 16 °C, with the average temperature being about 10 C.

We compiled the distribution ranges of *T. lasiopetalum* from sources including "Flora of Iran" (Mozaffarian 2007), "Flora Iranica" (Rechinger 1987), and Flora of Chaharmahal and Bakhtiari province (Mozaffarian 2017). We examined herbarium specimens from the D collection (acronym based on Thiers 2023) and documented their localities. During field surveys in 2023-2024, we established 4 to 5 sampling stations in each locality while ensuring occurrence points were recorded at least one kilometer apart to avoid spatial autocorrelation. We used a handheld GPS receiver (Garmin Map 62s) to record the longitude and latitude of each site and compiled a geographical distribution database. A total of 25 occurrence points for the species were recorded (Fig. 1).

Description

Perennial herbs, aromatic, 30-90 cm tall; caudex clothed with a papery base of old petioles. Stems branched, to 6 mm in diameter, profoundly sulcate, with acute papillate trichomes. Leaves undivided, abaxially-adaxially with short papillate trichomes, abaxially strongly nerved, with dense and long trichomes; basal leaves with long petiole, lamina orbicular or broadly ovate, 8-17 mm long, 6-16 mm wide, 3-lobed, grossly crenate-dentate at margin, cordate-truncate at base; upper cauline leaves much smaller, with an inflated ovate sheath. Rays of inflorescence 10-30, subequal, 2-10 cm, densely with short papillate trichomes; bracts ovate-lanceolate, few and short, often deciduous; bracteoles few, lanceolate. *Flowers* white, not radiant, petals villosulous outside. Ovary densely hairy. Styles pubescent. Fruits obovate-elliptic, 11-14 mm long, 9-10 mm width, retuse, densely and retrorsely scabrid-setulose; dorsal vittae filiform-subclavate, -¾ as long as mericarp; commissural vittae 2, as long as mericarp (Fig. 2), (Mozaffarian 2007).

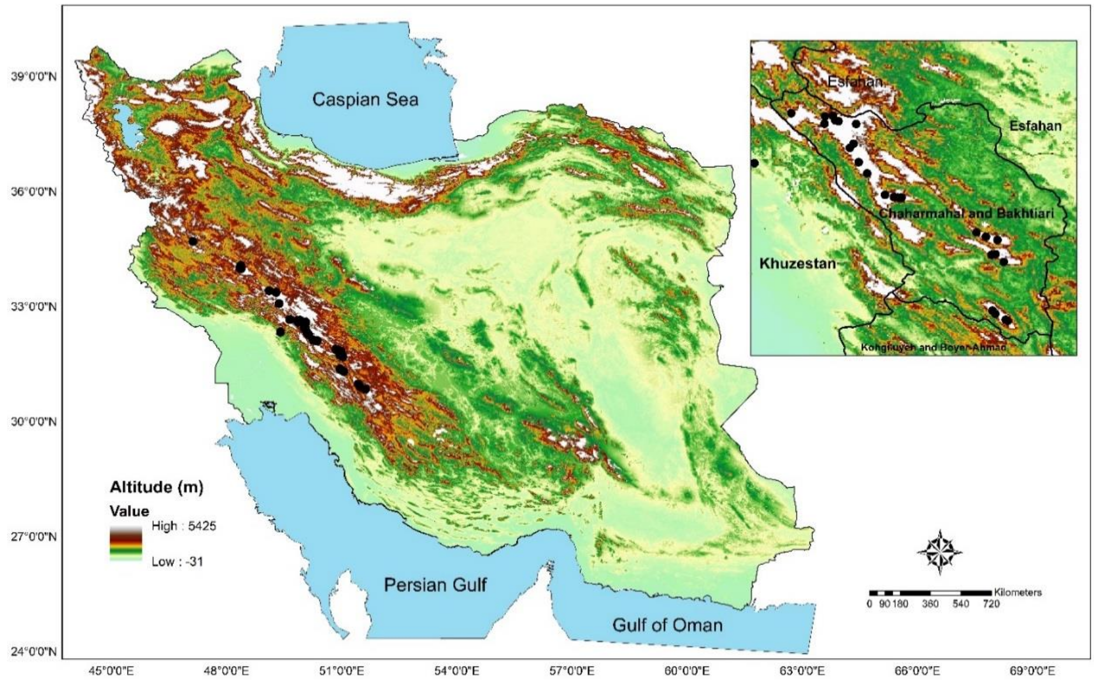

Fig. 1. Distribution of *T. lasiopetalum* in Iran (left side) and Chaharmahal and Bakhtiari province (right side). Black circles indicate the presence of the species.

Fig. 2. The natural habitat of the *T. lasiopetalum* in the heights of ZardKuh. Photo: AZ.

Environmental variables

We used 19 bioclimatic variables from the Chelsa climate database covering the period from 1979 to 2013 (Karger & al. 2017). The DEM map was obtained from the raster layer at www.worldgrids.org, and the aspect and slope maps were generated using ArcGIS 10.8 software. We also collected soil samples to analyze physico-chemical properties. Maps for each parameter were created using the Inverse Distance Weighted interpolation method and ArcGIS 10.8 software after analyzing soil samples from the studied areas where the species grow. To assess the potential impact of future climate changes on the distribution of the studied species, we used the CCSM4 atmospheric general circulation model with optimistic (RCP2.6) and pessimistic (RCP8.5) scenarios for the 2050s and 2070s. Raster layers of the CCSM4 model were obtained from http://www.ccafs-climate.org. The correlation between the variables was examined using the USDM software package in the R v3.2.3 software environment, and variables with a Variance Inflation Factor (VIF) greater than 10 were removed to prevent collinearity (Naimi & al. 2023). Finally, 18 variables were used for the modeling process (Table 1).

Table 1. Environmental variables used in the distribution modeling of *T. lasiopetalum*.

Code	Environmental variables (Unit)
Bio2	Mean Diurnal Range (Mean of monthly (max temp - min temp)) (°)
Bio3	Isothermality (BIO2/BIO7) (×100) (°)
Bio7	Temperature Annual Range (BIO5-BIO6) (°)
Bio8	Mean Temperature of Wettest Quarter (°)
Bio13	Precipitation of Wettest Month (mm)
Bio14	Precipitation of Driest Month (mm)
Bio15	Precipitation Seasonality (Coefficient of Variation) (mm)
Bio17	Precipitation of Driest Quarter (mm)
Bio18	Precipitation of Warmest Quarter (mm)
OC	Soil organic carbon content (gkg^{-1})
Clay	Clay content (g/kg (%))
Sand	Sand content (g/kg (%))
Silt	Silt content (g/kg (%))
EC	Electric conductivity ($dS\ cm^{-1}$)
ph	Soil acidity
Alt	Altitude (m)
Asp	Aspect (-)
Slope	Slope (°)

Species distribution modeling

The maximum entropy model (MaxEnt) was used to predict the current and future distribution of the *T. lasiopetalum* (Phillips & al. 2006). In total, 75% of the data was randomly used as training data, and 25% was used as test data to build the model. The distribution maps were obtained using MaxEnt software and 10,000 background points. The model's performance was evaluated using the area under the curve (AUC), and permutation importance values were used to determine the key environmental variables affecting species distribution. The AUC value is between 0 and 1, so the AUC value equal to 0.5 shows that the discrimination efficiency of the model is random, and the value of 1.0 indicates its high discrimination ability (Elith & al. 2006). The changes in species distribution were evaluated using R v3.2.3 software.

RESULTS

Based on our research findings, the AUC is greater than 0.9. This value demonstrates the model's excellent performance in predicting the preferred habitats of the species under study (Fig. 3).

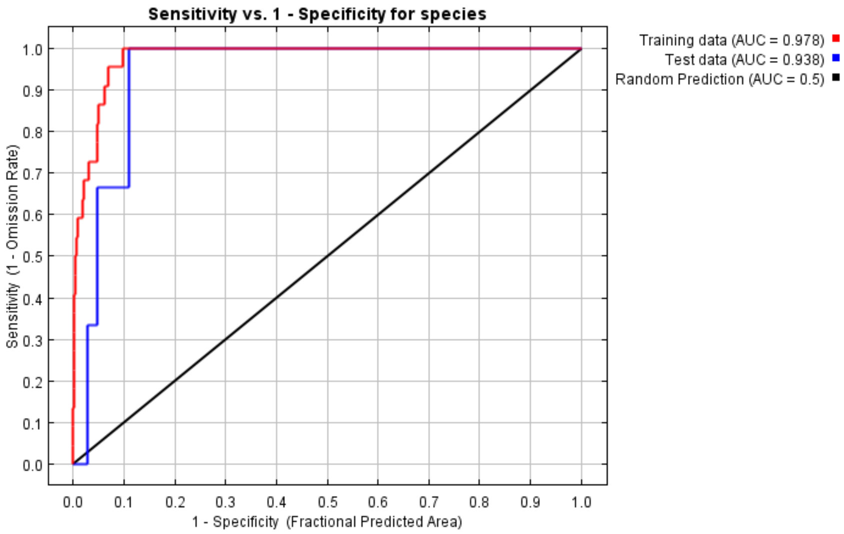

Fig. 3. Plot of the area under the ROC curve for validating the *T. lasiopetalum* habitat suitability model.

MaxEnt modeling predicts that approximately 2660 square kilometers, equivalent to 16.09% of the province's total area, could serve as potential habitat for the *T. lasiopetalum*. According to Fig. 4, the high elevation and alpine zones of Zardkuh, Kūh-e Mīlī, Kūh-e Garreh, Sabzkūh, Kūh-e Kallar, Kūh-e Rīg, and Kūh-e Aḩmad Līveh are suitable habitats for the growth and distribution of this species. Additionally, as depicted in Fig. 4, less than ten percent of the favorable habitats for this species are located in the four environmental protection areas, including the Sabzkūh protected area and limited parts of the protected Ghaysari and Helen areas.

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The study predicts that in response to climate change in the 2050s under the RCP2.6 scenario, about 20/11% will be added to the total favorable habitats of this species, increasing its range (Table 2 & Fig. 5). However, it is also expected that 2/41% of the species distribution range will decrease in the 2070s under the RCP2.6 scenario. Under the RCP8.5 scenario and in the 2050s, climate change is forecasted to have a positive effect, with approximately 23/38% added to the total favorable habitats of this species (Table 2 & Fig. 5). On the contrary, in the 2070s, and under the RCP8.5 scenario, a 13/68% decrease in distribution is anticipated (Table 3 & Fig. 5).

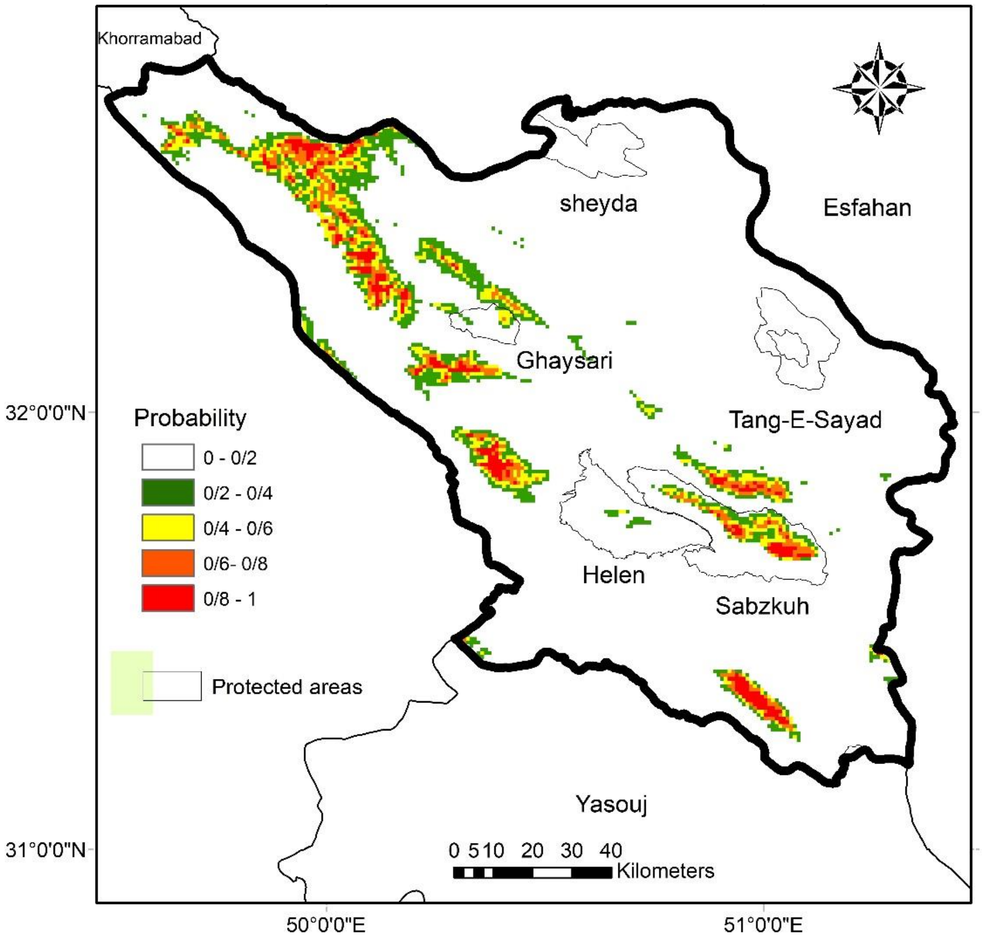

Fig. 4. Map of the present potential distribution of *T. lasiopetalum*.

Table 2. Percentage of changes in the suitable habitats of *T. lasiopetalum* under RCP 2.6 in the 2050s and 2070s.

Species	Time - Scenario											
	2.6-2050						2.6-2070					
	Gain (%)	Area (Km^2)	Loss (%)	Area (Km^2)	Change (%)	Area (Km^2)	Gain (%)	Area (Km^2)	Loss (%)	Area (Km^2)	Change (%)	Area (Km^2)
Tetrataenium lasiopetalum	24/62	655.00	4/51	120.00	20/11	535.00	9/21	245.00	11/62	309.00	-2/41	-64.00

Table 3. Percentage of changes in the suitable habitats of *T. lasiopetalum* under RCP 8.5 in the 2050s and 2070s.

Species	Time - Scenario											
	8.5-2050						8.5-2070					
	Gain (%)	Area (Km^2)	Loss (%)	Area (Km^2)	Change (%)	Area (Km^2)	Gain (%)	Area (Km^2)	Loss (%)	Area (Km^2)	Change (%)	Area (Km^2)
Tetrataenium lasiopetalum	28/05	746.00	4/66	124.00	23/38	622.00	3/27	87.00	16/95	451.00	-13/68	-364.00

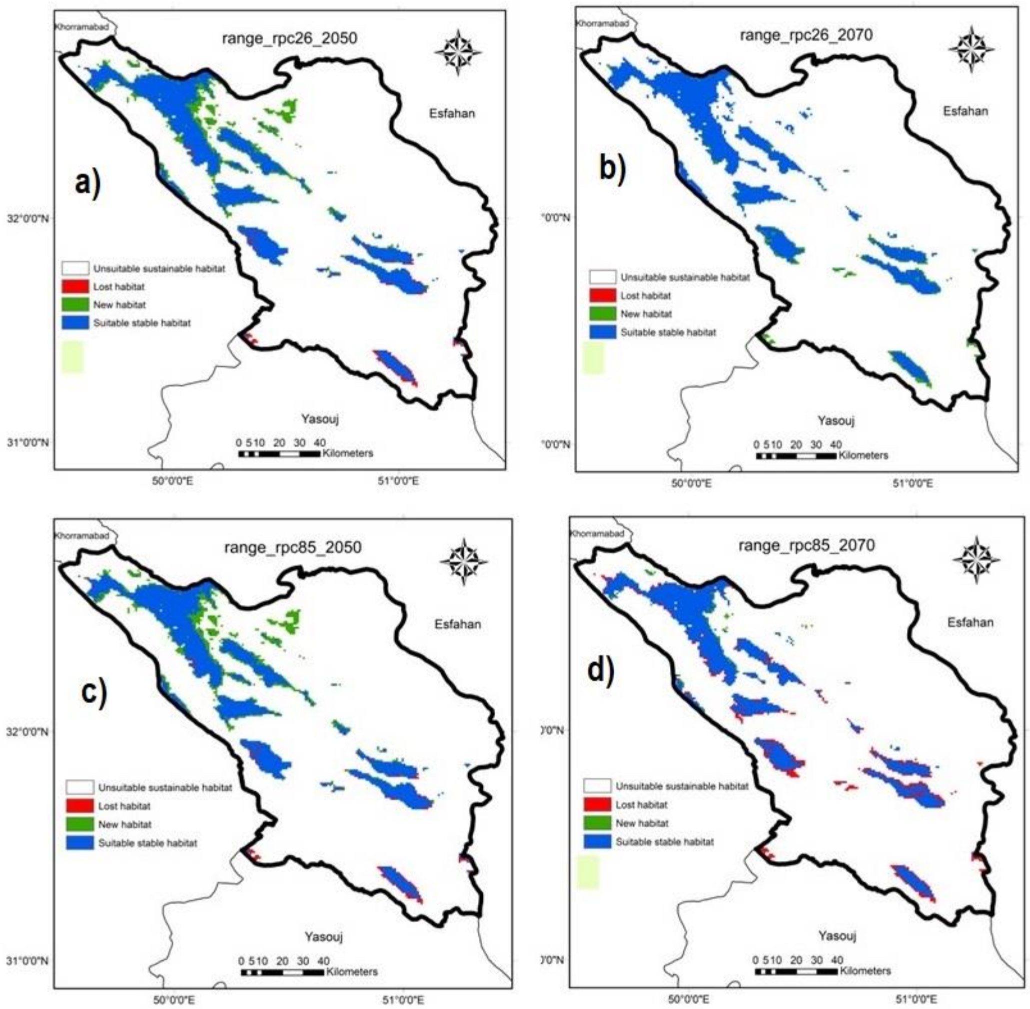

Fig. 5. Map of the potential distribution of *T. lasiopetalum* in the future. a, under RCP 2.6 scenario in the 2050s; b, under RCP 2.6 scenario in the 2070s; c, under RCP 8.5 scenario in the 2050s; d, under RCP 8.5 scenario in the 2070s.

Based on the permutation importance of pH (59.1%), soil organic carbon (10.4%), slope (5.8%), sand percentage (4.4%), altitude (4%), and precipitation in the wettest month (Bio13) (4%) are the most important environmental variables affecting species distribution (Fig. 6). Areas with a pH index between 5.6 and 5.8, soil organic carbon levels between 80% and 110%, and a slope percentage of less than 70% are favorable habitats for the occurrence of *T. lasiopetalum* in the study area. The model's output indicated a direct relationship between the presence of the species and altitude. As the altitude rises above 2,500 meters, the potential habitats for the species expand. The highest occurrences of this species were observed at altitudes ranging from 3,300 to 3,700 meters. Additionally, the most suitable habitats for the species have a precipitation level in the wettest month exceeding 270 mm and a sand percentage between 35% and 43%.

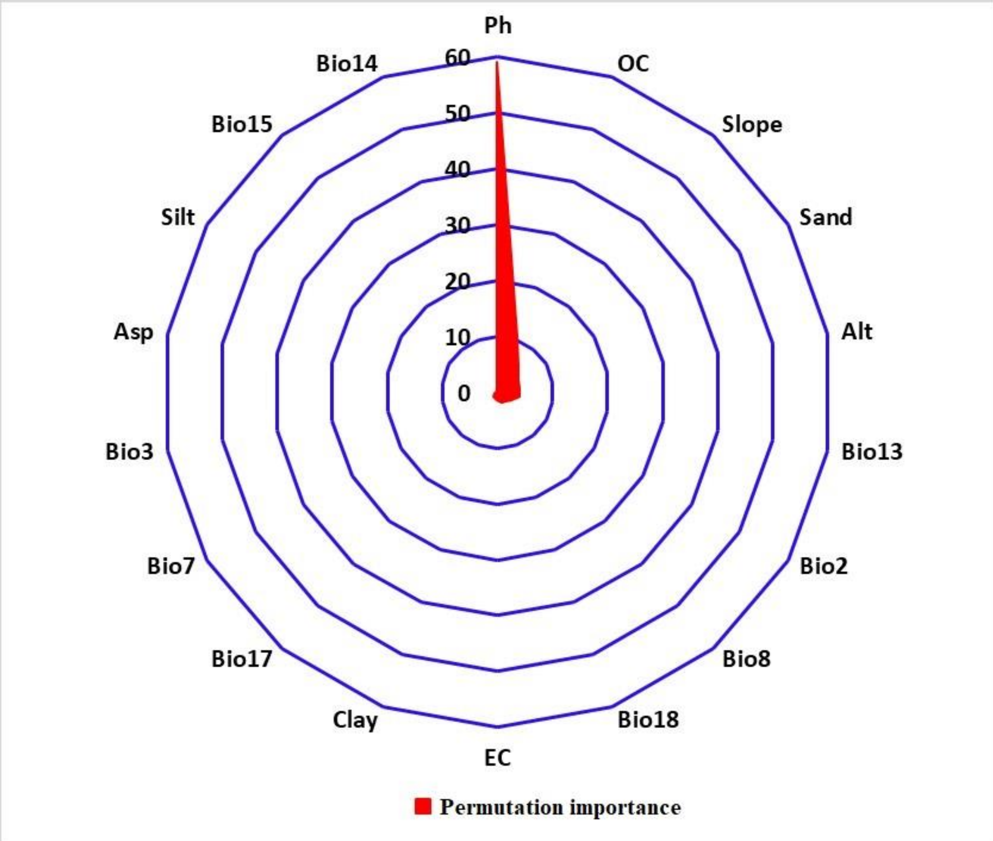

Fig. 6. Percentage of importance of environmental variables in the distribution of *T. lasiopetalum*.

DISCUSSION

This research utilized species distribution modeling to forecast the suitable habitats of the *T. lasiopetalum*. This approach assists in comprehending how species react to climate change and global warming. The study's results can benefit conservation, management, and further research on this species in the province and Iran. The study shows that the MaxEnt model has a highly accurate predictive capacity with AUC values exceeding 0.9. Other research on the potential distribution of *Pistacia atlantica* and *Crataegus azarolus* in Chaharmahal and Bakhtiari province also underscores the robust performance of the MaxEnt model (Naghipour Borj & al. 2019a; Naghipour & al. 2021a). According to the model output, this species is found in only 16.09% of the total area of the province, specifically in mountainous areas such as Zardkuh, Kūh-e Mīlī, Kūh-e Garreh, Sabzkūh, Kūh-e Kallar, Kūh-e Rīg, and Kūh-e Aḩmad Līveh. As a result, *T. lasiopetalum* has a limited distribution in the province, and local uncontrolled harvesting poses serious risks to its survival. The modeling results suggest that this species is expected to expand its distribution by the 2050s under optimistic and pessimistic scenarios. Our field observations reveal that the *T. lasiopetalum* is present in the mountainous habitats of the province at elevations between 1950-3700 m.a.b.s and is either absent or very scarce at higher altitudes, typically in the form of dry and extremely cold rock deposits. It is not found at lower altitudes, likely because it is sensitive to high temperatures. As the temperature is expected to rise in the 2050s, it seems that many habitats at higher altitudes, typically snow-covered or very cold and dry, will become more suitable for the growth and distribution of this species. This is especially true for Zardkuh, the largest habitat of *T. lasiopetalum*, being likely the strongest area for its distribution in the province. The amount of precipitation in the wettest season (Bio13) is the most important climatic factor affecting the distribution of the studied species. With increasing temperatures and warming of the earth, cold and dry habitats of this species are expected to become more humid, leading to a wider distribution. Consequently, the species is anticipated to expand its distribution in this decade and benefit from climate change. The Zagros mountains in the western part of Iran are home to high peaks such as Dena, Kūh-e Kallar, Zardkuh, Oshtorankuh, and Shahankuh, and are usually covered with snow throughout the year. Likely, the increase in temperature and reduction of permanent frost due to climate change in the coming years will provide favorable conditions for the growth and germination of species in the high snowy ecosystems of Zagros, leading to a wider dispersion of the species (Khajoei Nasab & al. 2022b). As the climate warms, it is expected to create more favorable conditions within the species' range, potentially increasing the opportunities for establishing plants at higher altitudes and expanding their distribution (Breshears & al. 2008). Multiple studies have indicated that the range of distribution of many mountain species may increase instead of decrease as a result of climate warming (Liang & al. 2018). For instance, a study by Khajoei Nesab & al. (2020) focused on five endemic species of the genus *Onosma* in Iran. The study indicates that these species, exclusively found in Zagros ecosystems, are expected to expand their distribution in response to climate change and will likely benefit from global warming. Additionally, research by Zeraatkar & Khajoei Nesab (2023) predicts that the *Prunus scoparia*, *P. haussknechtii* C.K.Schneid., and *P. lycioides* (Spach) C.K.Schneid. will likely increase in their favorable habitats in response to climate change in the coming years. The results of this study indicate that soil parameters and topographical factors are key environmental factors influencing the distribution of the studied species. Soil parameters such as organic carbon content, pH, and sand percentage significantly influence the distribution of the studied species. Soil organic carbon plays a fundamental role in soil fertility by facilitating nutrient availability, improving soil structure, enhancing moisture retention and root development, and increasing tolerance to variations in rainfall (Hartemink & McSweeney 2014). Soil texture is vital for plant growth because it influences water availability and fertility, affecting nutrient delivery to plant roots (Browning & al. 2008). Soil pH is a critical factor in soils because it regulates many chemical and biochemical processes. According to Oshunsanya (2019), changes in soil pH can have significant implications. Additionally, climate change, along with alterations in soil parameters, can lead to substantial shifts in the types of vegetation found in various regions (Afuye & al. 2021). Coarse-textured soils, like sandy and silty ones, lack moisture retention, which allows gravity to draw moisture deeper into the soil (Rajakaruna & Boyd 2008). Studies show that such soils contribute significantly to the expansion of some plant species (Craine et al., 2010). For example, Comole & al. (2021) demonstrated the key role of sandy soil in seedling establishment and its impact on the distribution of *Prosopis* shrubs in Australia and South Africa. Topographic factors, including elevation and slope, play a significant role in the distribution and diversity of vegetation and plant species in mountainous regions (Oke & Tompson 2015). These factors influence the spatial distribution of sunlight, heat, water, and soil nutrients (Feng & al. 2011). Among the climatic variables, only precipitation in the wettest month of the year is considered the most important environmental factor affecting the species' distribution. This suggests that the species has less dependence on temperature variables, making it resilient to temperature increases projected for the 2050s. Similar findings were reported in a study on 20 endemic species of the genus *Allium* in Iran, which indicated that 90% of the species in Zagros Mountain ecosystems would benefit from global warming due to their reliance on soil characteristics such as carbon percentage and organic matter (Khajoei Nasab & al. 2022b). Their low dependence on temperature factors will make them more resistant to future climate changes and lead to increased distribution. It is important to note that many mountain species, such as *Kelussia odoratissima* Mozaff., and *Ferulago* spp., are sensitive to climate change and are predicted to disappear in the future in response to global climate change (Abolmaali & al. 2017; Hosseini & al. 2024d). Since each region has its environmental conditions, species' responses in the different areas or mountains to climate change can vary. For example, as depicted in Fig. 4, this species may lose parts of their favorable habitats in the southern areas while expanding into more favorable habitats in the north and northwest in response to climate change. This is because global warming influences the migration of mountain species toward cooler climates at higher latitudes (Lenoir & Svenning 2013; Zu & al. 2021). Consequently, habitat loss and population declines may occur in lower latitudes or southern regions (Freeman & al. 2018; Morueta-Holme & al. 2015).

Several modeling studies conducted on various plant species across Iran highlight the impact of climate change. These studies predict that many plant species will migrate to higher altitudes or latitudes in response to climate changes. For example, Limaki & al. (2021) demonstrated that *Fagus orientalis* L. will migrate to higher altitudes in the Hyrcanian forests due to climate changes. Additionally, Khajoei Nasab & al. (2022a) predicted that *Echium amoenum* L. will also migrate to higher altitudes in response to global warming, leading to a loss of habitats at lower altitudes. Research by Hosseini & al. (2024a, b, c) also suggests the migration of some species and subspecies of thyme to higher altitudes. Studies in Chaharmahal and Bakhtiari province indicate that many plant species, including

Salvia hydrangea, *Prangos ferulacea* (L.) Lindl, *Prunus scoparia*, *Quercus brantii* Lindl., and *Astragalus verus* Olivier, will undergo upland migration in the future in response to climate change (Haidarian Aghakhani & al. 2017, 2018; Ghehsareh Ardestani & Heidari Ghahfarrokhi 2021; Sheikhzadeh Ghahnaviyeh & al. 2021; Babaei & al. 2022).

Our findings indicate that *T. lasiopetalum* will likely experience a reduced distribution in response to climate change in the 2070s. The rising temperatures during this period are expected to result in the decline of the population residing at lower altitudes. Cold-adapted Mountain species are also facing challenges due to climate warming and increased competition from species that previously inhabited lower altitudes but have migrated to higher elevations as a response to climate change (Rana 2014). The heightened migration of plant species to higher altitudes may give rise to new plant communities and lead to changes in ecosystem functioning. Additionally, mountain species are compelled to move to the highest altitudes when temperatures exceed their optimal range, leading to the "summit trap phenomenon," which hinders their migration to the mountaintop and puts them at risk of destruction (Salick & al. 2009). Studies conducted on *Hordeum bulbosum* L., *Stipa hohenackeriana*, and *Carataegus azarolus* in the Chaharmahal and Bakhtiari province also suggest that these species will undergo a reduced distribution in response to climate change, potentially losing their suitable habitats (Teimori Asl & al. 2020; Naghipour & al. 2021a; Hosseini & al. 2022).

Our findings indicate that climate change is likely to significantly affect the distribution and potential habitat suitability of *T. lasiopetalum*, which could lead to important ecological and socioeconomic consequences. Additionally, indiscriminate harvesting poses a serious threat to the survival of this plant species, highlighting the need for protective measures to prevent its extinction and destruction. Furthermore, the research identifies potentially suitable habitats where this species can be planted. It's important to note that less than ten percent of the favorable habitats for this species are located in the environmental protection zones. To prevent its extinction, it is suggested this research guide the conservation authorities in developing appropriate strategies for protection.

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