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# Modeling the Impact of Climate Change on the Spatial Distribution of the Endangered Medicinal Plant *Ferula assa-foetida* L. in Kerman Province

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## ABSTRACT

Climate change significantly affects the habitats of species by altering plant distributions and their interactions with environmental factors. This study aimed to model the spatial distribution of the endangered medicinal plant *Ferula assa-foetida* L. under current and future climate scenarios in Kerman Province. Species occurrence locations were recorded using Global Positioning System (GPS) tracking. Habitat suitability modeling was conducted for two time periods: the present and the future (2050). Environmental variables incorporated into the models included climatic, physiographic, and land use factors relevant to the study area. To predict future distribution patterns based on climatic variables, two climate models HadGEM3-GC31-LL and MRI-ESM2.0 were employed under two Shared Socioeconomic Pathway (SSP) scenarios: SSP245 and SSP585. The Maxent model was used for species distribution modeling, achieving excellent predictive performance with an Area Under the Curve (AUC) value of 0.966. Among the environmental variables, BIO9 (Mean Temperature of Driest Quarter), BIO19 (Precipitation of Coldest Quarter), and BIO11 (Mean Temperature of Coldest Quarter) contributed most significantly to habitat suitability. Projections for 2050 indicate a drastic reduction in suitable habitats for *F. assa-foetida*. Specifically, under the HadGEM3-GC31-LL, suitable habitats are expected to decrease by 97.49% and 99.91% under SSP245 and SSP585 scenarios, respectively. Similarly, the MRI-ESM2.0 model predicts reductions of 97.51% and 98.26% under the same scenarios. These findings highlight the urgent need for targeted management strategies to mitigate the impacts of climate change and prevent the potential local extinction of this species. Furthermore, understanding the plant's adaptive mechanisms may provide insights into its resilience and inform conservation efforts.

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## 1. Introduction

Various characteristics including climatic, topographic, soil, land use, and biological factors- are among the most influential determinants affecting the distribution of plant species across different spatial scales. Among these, climate stands out as one of the most critical factors influencing plant species distribution in diverse regions (Byeon *et al*., 2018). Climate generally represents the average weather patterns of a specific location or region over several decades (Su *et al*., 2021). Climate change impacts species' habitats by altering plant species themselves and their interactions with other organisms, which subsequently leads to changes in ecosystem structure, function, and services (Fedele *et al*., 2019). Ecosystems, particularly rangeland ecosystems, are highly sensitive to climate change. Since plants and animals in rangelands exist near the threshold of water and heat stress, even minor variations in temperature and precipitation regimes, or changes in the frequency and intensity of extreme climatic events, can significantly affect plant species composition, distribution, dispersal, and productivity (Antoine *et al*., 2000).

Given the global occurrence of climate change, Iran is also expected to experience significant climatic shifts, making climate change one of the most pressing environmental challenges facing humanity (Alavipanah *et al*., 2022). Projections suggest that temperatures in most regions of Iran may increase by 2–3ºC (Jafari, 2014). It has been predicted that a global average temperature rise of 1.5–2.5 ºC could place 20–30% of plant and animal species at risk of extinction. Furthermore, carbon sequestration by ecosystems is expected to increase until the mid-21st century, after which it may weaken or reverse. Consequently, ecosystems may transition from carbon sinks to carbon sources, releasing carbon dioxide into the atmosphere and thereby exacerbating climate change (Motamedi *et al*., 2022).

These climatic changes are anticipated to cause a significant reduction in humid climate zones and an expansion of arid regions, leading to a marked decrease in humidity within natural areas (Jalili, 2021). This shift will likely accelerate desertification processes. Ultimately, rising temperatures will reduce bioclimatic comfort, forcing some plant and animal species that cannot adapt to migrate from their native habitats or face gradual extinction (Ferrarini *et al*., 2014). Therefore, it is essential to further investigate these complex relationships (Hosseini Khezr Abad *et al*., 2024). Studies conducted to investigate the effects of climate change on the distribution of plant species and communities show that in the 2030s and 2080s, the distribution range of many plant species and plant communities will decrease significantly (Krebs, 2014). The trend in changes to their ecological range indicates that in the coming years, under the influence of climate change, we will witness the establishment of plant species at higher altitudes, while the probability and possibility of the presence of plant species at lower altitudes will also decrease (Motamedi *et al*., 2022). Changes that occur in the geographical range of plant species represent a form of adaptation for durability and sustainability against climate change (Babaei *et al*., 2022). Therefore, predicting the effects of future climate change on the distribution of valuable plant species is of great importance for their management, effective protection, and assessment of the level of threats (Rana *et al*., 2017).

Global climate change is profoundly altering the structure and function of natural ecosystems, posing a significant threat to biodiversity worldwide. Predicting how species will respond to these changes is a fundamental challenge, given the inherent complexity of ecological systems. To address this, Species Distribution Models (SDMs) have emerged as critical analytical tools. SDMs enable researchers to project potential shifts in species habitats under various climate scenarios, thereby providing a scientific basis for developing and prioritizing effective conservation and adaptation strategies (Amiri *et al*., 2019). Moreover, SDMs enable the quantification of species-environment relationships and facilitate the prediction of spatial distributions based on these relationships (Pliscoff *et al*., 2014). Various SDMs have been developed to assess the distribution of plant species and to identify the environmental factors influencing their distribution. Some models utilize only species presence data, while others incorporate both presence and absence data (Momeni-Damaneh *et al*., 2021).

One of the most widely used algorithms for modeling species distribution based on occurrence points is the maximum entropy (Maxent) method, which is a presence-only modeling approach (Zare Chahoki and Abbasi, 2017). Maxent is commonly employed to predict both current and future species distributions (Fourcade *et al*., 2014). A key advantage of the Maxent model is its ability to generate robust and accurate predictions even when the number of occurrence points is limited (Elith *et al*., 2011). Additionally, Maxent allows for the ranking of environmental variables according to their relative importance in influencing species distribution, using optimized model parameters (Corović *et al*., 2018; Petrosyan *et al*., 2019). *Ferula assa-foetida* L. is an endangered herbaceous, perennial, and monocarpic plant belonging to the Asteraceae family (Khodashenas, 2022; Zargari, 1997). It typically grows in barren areas with dry, sandy soils rich in calcareous compounds (Integrated Rangeland Management Plan for Abdoran Rangeland, 2021). The plant's root produces and stores a valuable sap, which is harvested by spiking and serves as an important source of income for local villagers and farmers. The stem is robust and produces crown-shaped leaves that lie close to the ground surface during the first five years of growth (Mozaffarian, 2000). The natural growing period of *F. assa-foetida* lasts approximately 2.5 months, beginning around mid-March, with leaves turning yellow from mid-May to early June (Rajbian *et al*., 2007). Propagation occurs exclusively through seeds (Raghavan, 2007). The gum extracted from *F. assa-foetida* is widely used in traditional medicine to treat digestive disorders (Abyar *et al*., 2016). In Kerman province, local communities utilize this gum to alleviate various digestive ailments, including the elimination of intestinal parasites and relief from bloating. It is also believed to counteract bodily coldness and improve eyesight. Economically, the plant is valuable to local populations, who derive significant income from the sale of its gum.

In recent years, numerous studies have investigated the impact of climate change on the distribution of *Ferula assa-foetida* species. For instance, Momeni Damaneh *et al*. (2021) predicted suitable habitats for *F. assa-foetida* L. in northeastern Iran, demonstrating high model accuracy with an Area Under the Curve (AUC) value of 0.97 using the maximum entropy model. Similarly, Bahreininejad *et al*. (2023) modeled the potential habitat of *F. assa-foetida* in Isfahan province using the maximum disorder model, reporting an (AUC) of 0.962, indicative of robust model performance. Variable importance analysis via the Jackknife test revealed that slope percentage, annual temperature range, annual precipitation, and precipitation during the coldest season are the most influential factors affecting the species' distribution. Complementing these findings, Iranmanesh *et al*. (2025) identified seasonal temperature fluctuations, total precipitation in the warmest season, and total precipitation in the coldest season as key contributors to habitat suitability modeling for *F. assa-foetida* in southern Iran. Additional research on this species has been conducted by Abdollahzadeh *et al*. (2024) and Shadmanfar (2015).

Beyond *F. assa-foetida*, related studies have explored the distribution of other species, including *Bromus tomentellus* Boiss (Bazrmanesh *et al*., 2018), *Xanthium italicum* (Zhang *et al*., 2021), *Meconopsis punicea* (Shi *et al*., 2022), *Fritillaria imperialis* (Naghipour *et al*., 2019), the medicinal plants *Echium amoenum* and *Echium italicum* (Khajoei Nasab *et al*., 2022), and *Dracocephalum kotschyi* (Ghahsareh Ardestani *et al*., 2024). Despite the endangered status and significant medicinal and economic value of *F. assa-foetida*, relatively few studies have addressed its future distribution under climate change scenarios. Most existing research has focused solely on current habitat suitability. Therefore, the present study aims to model the spatial distribution of this endangered species under future climate scenarios SSP245 and SSP585, employing two climate models HadGEM3-GC31-LL and MRI-ESM2.0 in Kerman province.

## 2. Materials and Methods

### *2.1. Study Area*

The present study was conducted in the rangelands of Kerman Province, located in southeastern Iran. This province covers more than 11% of Iran's total land area, spanning approximately 181,737 km² and making it the largest province in the country (Afsharipour, 2019). Geographically, Kerman Province lies between longitudes 54°21′E to 59°34′E and latitudes 26°29′N to 31°58′N relative to the Greenwich Meridian (Kerman Province Management and Planning Organization, 2016). It is bordered by Yazd and South Khorasan provinces to the north, Sistan and Baluchestan Province to the east, Hormozgan Province to the south, and Fars Province to the west. The province features diverse climatic conditions, encompassing more than 12 main and sub-climates (Kerman Province Management and Planning Organization, 2016). Elevations range from 132 m to 4,318 m above sea level, resulting in an altitudinal variation of approximately 4,200 m. The average annual rainfall is 123.4 mm, and the mean annual temperature is 21.2°C (Integrated Rangeland Management Plan for Abdoran Rangeland, 2021).

### *2.2. Sampling method and selection of environmental variables*

To identify the habitats of *Ferula assa-foetida* in Kerman Province, consultations were conducted with relevant departments, including inquiries with natural resources experts and researchers. This process revealed nine reference habitats comprising summer, transitional, and winter rangelands distributed across various counties in the province. Field surveys were carried out during the spring and summer of 2024, during which the geographical coordinates of *F. assa-foetida* occurrences were recorded using a (GPS) device (Figure 1). Presence locations were selected in areas where the species was not only dominant but also formed at least one contiguous patch covering a minimum of 1 km². To minimize spatial autocorrelation, sampling points were spaced at least 1 km apart (Haidarian Aghakhani *et al*., 2017; Nazari *et al*., 2022). In total, 256 occurrence records for *F. assa-foetida* were documented across the rangelands of Kerman Province.

Species distribution modeling was performed for two temporal scenarios: the baseline (current) period and a future period centered on 2050 (representing the average conditions from 2041 to 2060). Environmental predictors included climatic, physiographic, and land-use variables relevant to the study area. Nineteen bioclimatic variables associated with temperature and precipitation (Table 1) and a digital elevation model (DEM) layer for the region were obtained in downscaled form at 30 arc-second resolution from the WorldClim 2 database (Fick & Hijmans, 2017).

Physiographic variables were derived from a digital elevation model (DEM). Slope percentage and aspect (slope direction) maps were generated using the DEM and incorporated alongside elevation data. Land use data were extracted from a layer provided by the Natural Resources and Watershed Management Organization of Iran. To assess and predict the future distribution of the study species, climatic variables were obtained under two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) scenarios from the HadGEM3-GC31-LL and MRI-ESM2-0 global climate models. These models were selected as the most suitable for simulating temperature and precipitation patterns across Iran (Abbasian *et al.*, 2019; Zareian *et al*., 2023).

All environmental layers (climatic, topographic, and land use) were subsequently standardized for spatial extent, pixel resolution, and coordinate reference system using ArcGIS 10.3 (Molaei *et al*., 2024).

Prior to modeling, multicollinearity among environmental layers was evaluated using Pearson's correlation coefficient in SPSS software (Sheikhzadeh Ghahnaviyeh *et al*., 2021). Variable pairs exhibiting correlations greater than 0.80 were identified, and selections were made based on prior ecological studies emphasizing the importance of climatic factors (Momeni Damaneh *et al*., 2021; Bahreininejad *et al*., 2023). Ultimately, 10 variables were retained as model inputs: land use (Landuse), aspect, slope percentage, isothermality (BIO3), temperature seasonality (BIO4), mean temperature of driest quarter (BIO9), mean temperature of coldest quarter (BIO11), precipitation seasonality (coefficient of variation; BIO15), precipitation of driest quarter (BIO17), and precipitation of coldest quarter (BIO19).

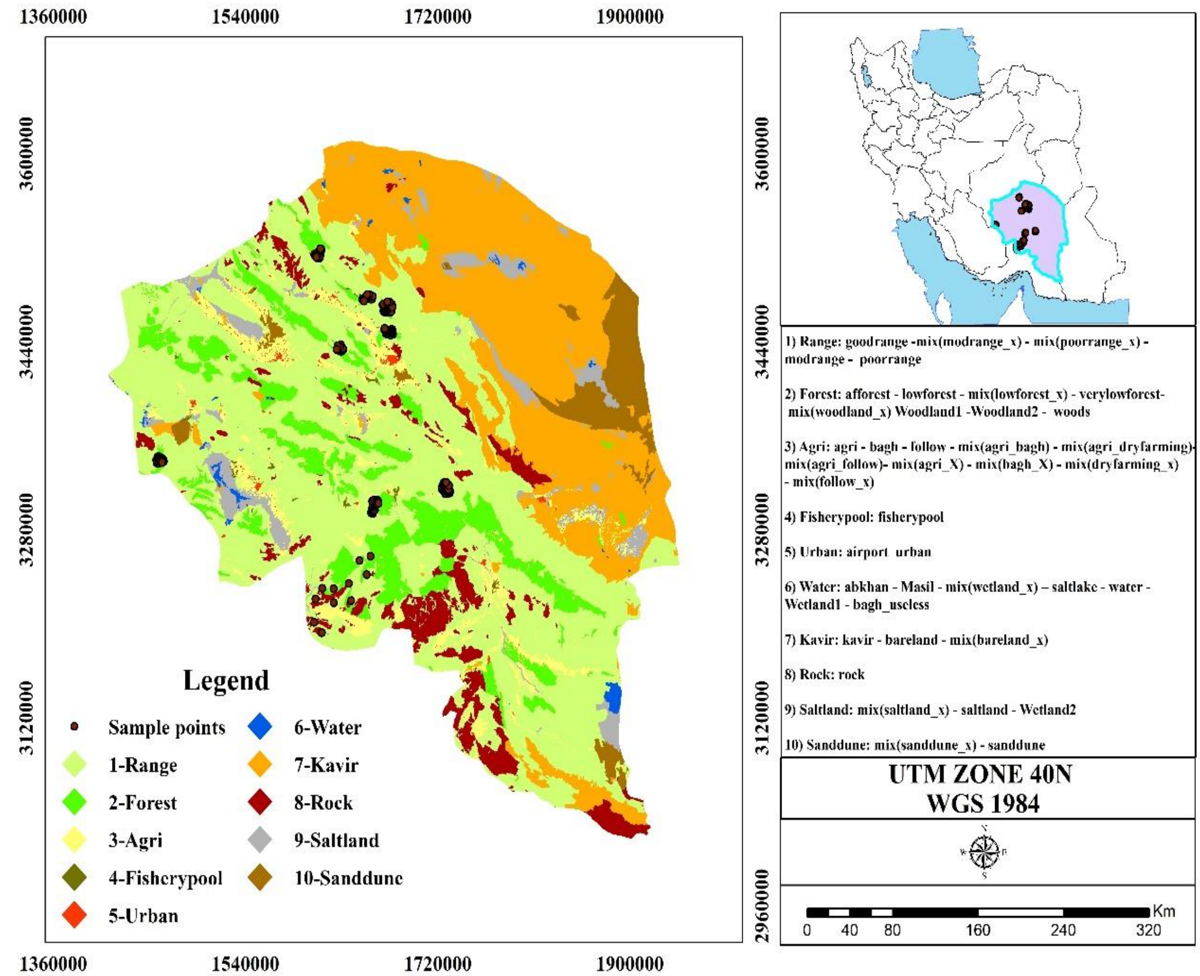


**Figure 1.** Location of *Ferula assa-foetida* sampling sites in Kerman Province.

**Table 1.** Description of bioclimatic variables

| Abbreviation | Variable description | Abbreviation | Variable description |
|---|---|---|---|
| $BIO_1$ | Annual Mean Temperature | $BIO_{11}$ | Mean Temperature of Coldest Quarter |
| $BIO_2$ | Mean Diurnal Range<br>(Mean of monthly (max temp - min temp)) | $BIO_{12}$ | Annual Precipitation |
| $BIO_3$ | Isothermality (BIO2/BIO7) (×100) | $BIO_{13}$ | Precipitation of Wettest Month |
| $BIO_4$ | Temperature Seasonality<br>(standard deviation ×100) | $BIO_{14}$ | Precipitation of Driest Month |
| $BIO_5$ | Max Temperature of Warmest Month | $BIO_{15}$ | Precipitation Seasonality<br>(Coefficient of Variation) |
| $BIO_6$ | Min Temperature of Coldest Month | $BIO_{16}$ | Precipitation of Wettest Quarter |
| $BIO_7$ | Temperature Annual Range (BIO5-BIO6) | $BIO_{17}$ | Precipitation of Driest Quarter |
| $BIO_8$ | Mean Temperature of Wettest Quarter | $BIO_{18}$ | Precipitation of Warmest Quarter |
| $BIO_9$ | Mean Temperature of Driest Quarter | $BIO_{19}$ | Precipitation of Coldest Quarter |
| $BIO_{10}$ | Mean Temperature of Warmest Quarter | | |

### *2.3. Species distribution modeling in Maxent*

We employed the Maximum Entropy (Maxent) model to predict the potential distribution of under current and future climate conditions. Maxent was selected for its robust performance with presence-only data and its accuracy with small sample sizes (Elith *et al*. 2011). The model was run using species occurrence records and bioclimatic and environmental variables sourced from WorldClim. Model performance was evaluated using the (AUC). A threshold value that maximized prediction accuracy based on the (AUC) was applied to convert the continuous habitat suitability map into a binary (suitable/unsuitable) distribution map (Thuiller *et al*., 2016). The relative contribution of each environmental variable was assessed using a Jackknife test. To project the species' distribution for the year 2050, we utilized two climate change scenarios from the Coupled Model Intercomparison Project Phase 6 (CMIP6): SSP245 (intermediate emissions) and SSP585 (high emissions). These scenarios were derived from two global climate models: HadGEM3-GC31-LL. and MRI-ESM2.0. Future projections were generated using the model parameters calibrated for the current climate. Changes in habitat distribution were quantified by comparing the current and future binary maps in (GIS) to identify areas of habitat expansion, contraction, and stability (Nazari *et al*., 2022).

### *2.4. Model evaluation*

To ensure model robustness, we employed a repeated random sub-sampling validation approach. The model was calibrated over 15 iterations. In each iteration, the data were randomly partitioned into a 75% training set and a 25% test set (Phillips and Dudík, 2008). Model performance and predictive accuracy were evaluated using the area under the Receiver Operating Characteristic (ROC) curve, or (AUC). The (AUC) index quantifies the model's ability to discriminate between suitable and unsuitable habitats for the species, with values derived from a confusion matrix of prediction errors (Phillips and Dudík, 2008; Nazari *et al*., 2022). The results of this evaluation are presented in Table 2.

Regarding the ROC index, the true positive rate (equation 1) and false positive rate (equation 2) are calculated based on the following relationships, respectively:

equation 1) TP[1]= a/(a+c)
equation 2) FP[2]= b/(b+d)

**Table 2.** Confusion Matrix of the results obtained from the model

| Ground reality / Model prediction | Presence of species | Absence of species |
|---|---|---|
| Presence of species | a | b |
| Absence of species | c | d |

Model performance was evaluated by the Area Under the Curve (AUC) of the Receiver Operating Characteristic (ROC). According to the classification of Franklin (2010), the diagnostic power of the model was categorized as follows: excellent (AUC > 0.9), acceptable ($0.7 \leq$ AUC $\leq 0.9$), or poor (AUC < 0.7).

## 3. Results

### *3.1. Validity of model*

The performance of the Maxent model, evaluated using the (AUC), was excellent for predicting the potential distribution of *Ferula assa-foetida*. The model attained an AUC value of 0.966 (Figure 2), indicating a high degree of predictive accuracy.

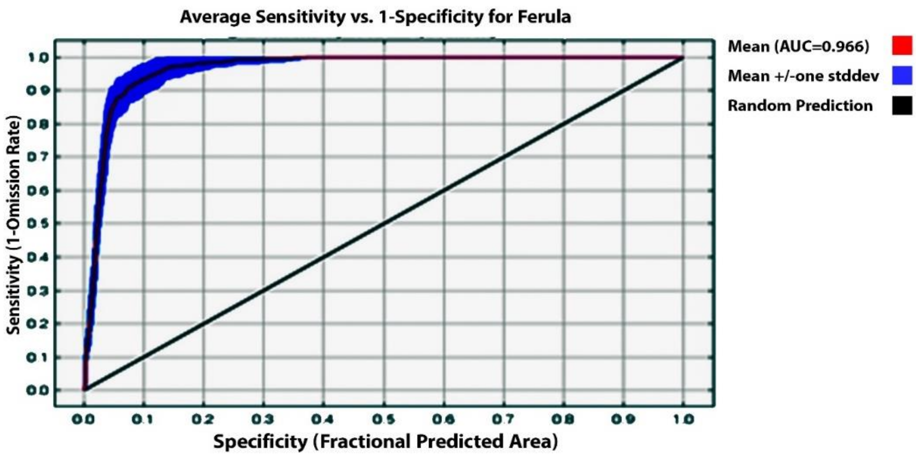


**Figure 2.** ROC curve for model evaluation

### *3.2. The importance of environmental factors affecting the distribution of the F. assa-foetida species*

The Maxent model analysis identified the relative contribution of key environmental variables in predicting habitat suitability for *Ferula assa-foetida*. (Figure 3). The mean temperature of the driest quarter (BIO9), precipitation of the coldest quarter (BIO19), and the mean temperature of the coldest quarter (BIO11) were the most influential factors, collectively

1 True Positive Rate
2 False Positive Rate

representing the primary determinants of suitable habitat (Figure 4). In contrast, slope aspect, precipitation of the driest quarter (BIO17), and slope percentage had the lowest contributions to the model.

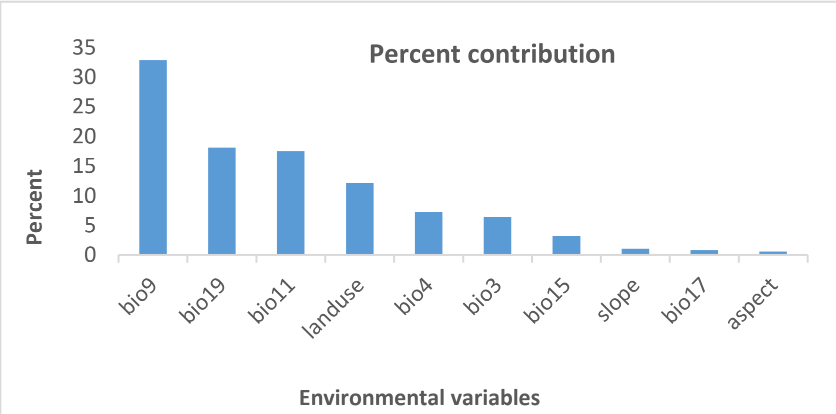


**Figure 3.** Percentage contribution of environmental variables affecting the distribution of *F. assa-foetida*

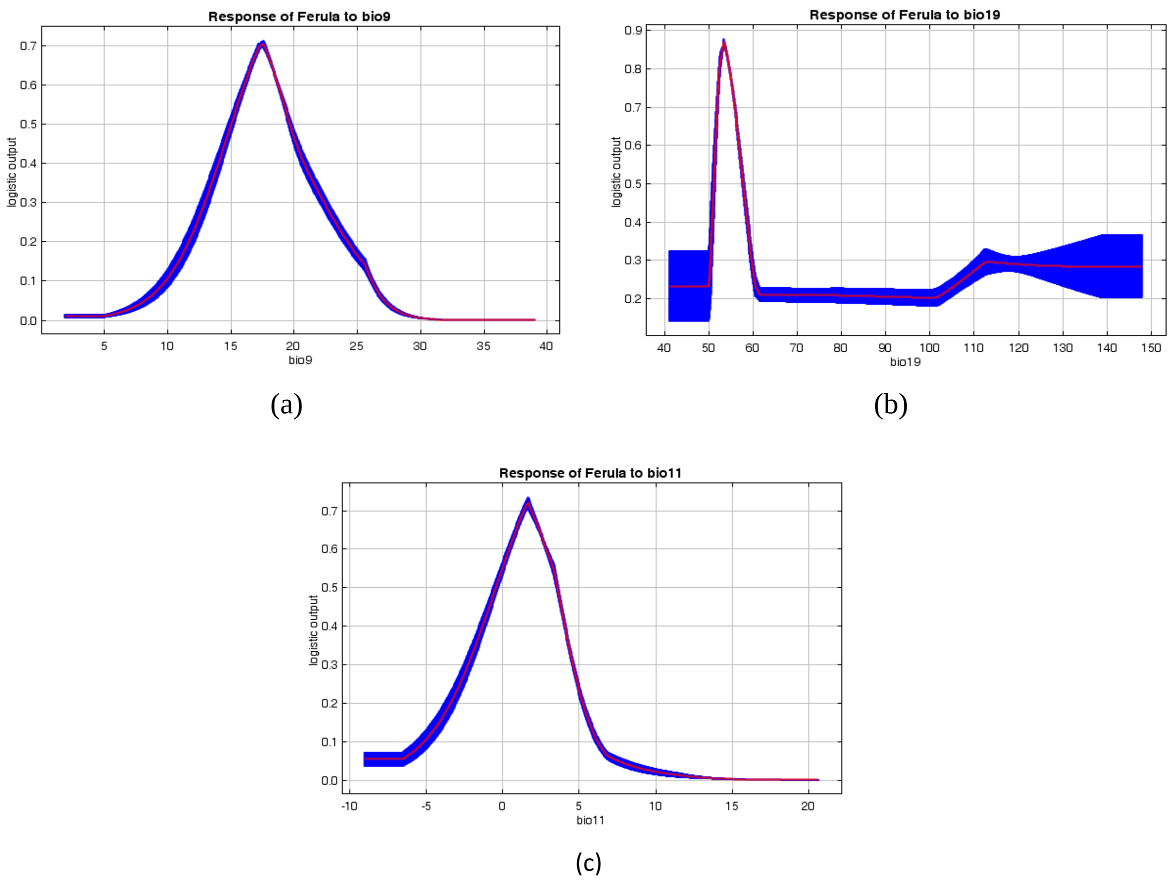


**Figure 4.** Response curve of the *F. assa-foetida* to the variables a) $BIO_9$ b) $BIO_{19}$ c) $BIO_{11}$

The Maxent model was employed to evaluate the current habitat suitability for *Ferula assa-foetida* within the study area. The model output, presented in Figure 5, depicts the spatial distribution of areas suitable for the species' occurrence. Suitability is expressed as a probability of occurrence, with values ranging from 0 (unsuitable) to 1 (optimal). A threshold probability of 0.2992, derived from the model, was applied to distinguish suitable from unsuitable habitats. As illustrated in Figure 5, the geographic extents identified as suitable habitat (i.e., probability of occurrence ≥ 0.2992) are highlighted in green.

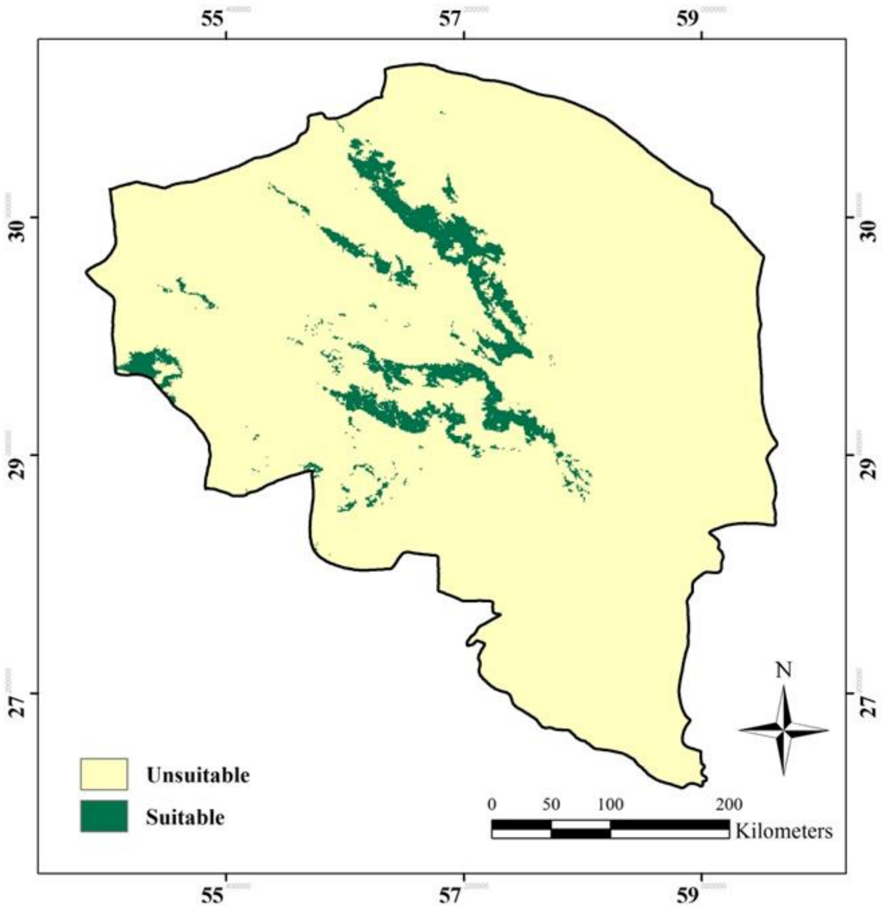


**Figure 5:** Habitat suitability map for the species *F. assa-foetida* under current climatic conditions

### *3.3. Changes in the the distribution range of the F. assa-foetida species under the influence of climate change*

Projections of the future distribution of *F. assa-foetida* for 2050, generated with the HadGEM3-GC31-LL and MRI-ESM2.0 models under SSP245 and SSP585 scenarios, reveal significant shifts in range suitability (Figure 6). The model outputs were categorized to distinguish between different types of range dynamics: stable suitable habitats (areas that remain suitable from the present to the future), habitat loss (areas where the species is currently present but will become unsuitable), habitat gain (areas that become newly suitable), and stable unsuitable habitats (areas that remain unsuitable under both time frames).

Model projections indicate that climate change will cause substantial alterations to the suitable habitat range of *Ferula assa-foetida* in Kerman province by the year 2050. The results from both climate models consistently forecast a severe, net reduction in suitable area. As detailed in Table 3, projections from the HadGEM3-GC31-LL model predict a near-total loss of suitable habitat. Under the SSP245 scenario, 97.49% of the current suitable habitat is projected to be lost, with only a 1.25% gain in new areas. The more extreme SSP585 scenario projects a 99.91% habitat loss against a minimal 0.16% gain. Similarly, estimates from the MRI-ESM2.0 model confirm this trend of dramatic habitat contraction. Under the SSP245 scenario, a 97.51% reduction is projected, partially offset by a 7.76% expansion into new regions. For the SSP585 scenario, the model projects a 98.26% habitat loss, with a 1.81% gain. In conclusion, the ensemble of model projections strongly suggests that the future climate conditions in Kerman province will lead to the near-complete destruction of the suitable habitat for *F. assa-foetida*.

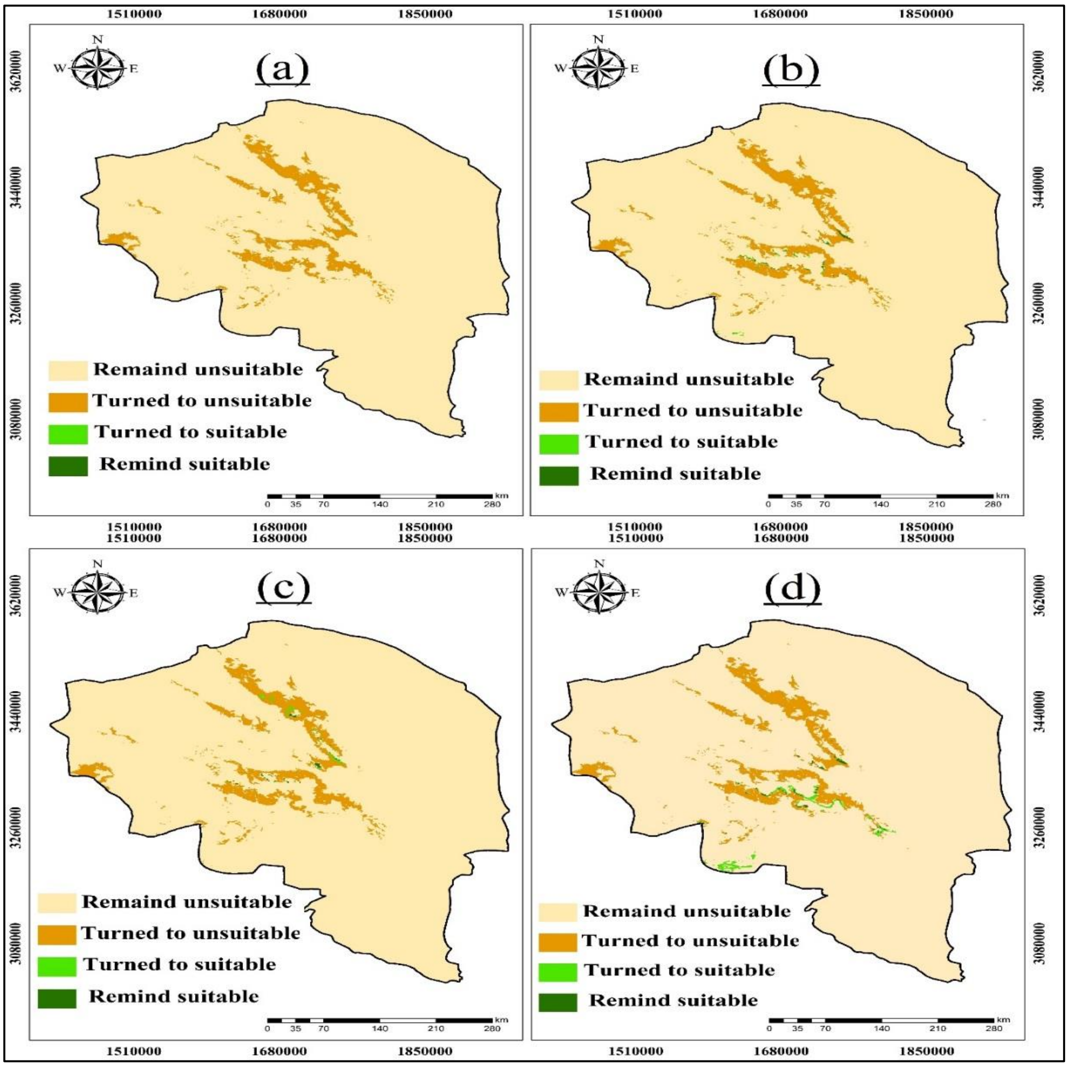


**Figure 6.** Projected changes in the distribution range of *Ferula assa-foetida* in Kerman province by 2050 under different climate change scenarios. Panels show: (a) changes projected under the SSP245 scenario using the HadGEM3-GC31-LL. model; (b) changes under the SSP585 scenario using the HadGEM3-GC31-LL model; (c) changes under the SSP245 scenario using the MRI-ESM2.0 model; and (d) changes under the SSP585 scenario using the MRI-ESM2-0 model.

**Table 3:** Projected Changes in Habitat Suitability for *F. assa-foetida* by 2050, Modeled under HadGEM3-GC31-LL and MRI-ESM2-0

| Model | Scenario | Year | Gain (%) | Change in current suitable habitat (%) |
|---|---|---|---|---|
| HadGEM3-GC31-LL | SSP245 | 2050 | 1.25 | -96.24 |
| HadGEM3-GC31-LL | SSP585 | 2050 | 0.16 | -99.75 |
| MRI-ESM2-0 | SSP245 | 2050 | 7.76 | -89.74 |
| MRI-ESM2-0 | SSP585 | 2050 | 1.81 | -96.45 |

## 4. Discussion

Our evaluation of the Maxent model for predicting the habitat suitability of *Ferula assa-foetida* yielded an (AUC) value of 0.966, indicating excellent predictive performance. This finding aligns with previous studies that have successfully utilized the Maximum Entropy approach for modeling species distribution in similar contexts. For instance, Momeni Damaneh *et al*. (2021) reported a comparable (AUC) of 0.97 for modeling *F. assa-foetida* L. in northeastern Iran, while Hosseini *et al*. (2024) confirmed the model's robustness in assessing climate change impacts on *Thymus* species in Iran. The high performance of Maxent is consistent with its theoretical advantages; as it relies solely on presence data, it avoids the complexities associated with models requiring both presence and absence records (Phillips *et al*., 2006). Furthermore, Maxent is recognized for its high efficiency and relative insensitivity to sample size variations compared to other modeling techniques (Elith *et al*., 2006).

The model identified temperature-related variables as the primary determinants of habitat suitability for *F. assa-foetida*. Specifically, the temperature of the driest season, the total precipitation of the coldest season, and the mean temperature of the coldest season contributed the most to the model. The collective contribution of temperature-based variables was greater than that of precipitation-based variables. This can be physiologically justified by the critical role of temperature in breaking seed dormancy and facilitating germination in *F. assa-foetida* (Rajbian *et al*., 2007; Norouzian *et al*., 2016). This result underscores that the species' distribution is more constrained by thermal thresholds than by moisture availability in the study area. In general, distribution patterns of plant species are profoundly influenced by macroclimatic conditions, with temperature and precipitation consistently identified as key drivers (Breshears *et al*., 2005; Amissah *et al*., 2014; Moraitis *et al*., 2019).

Our projections indicate that climate change will precipitate extensive alterations in the suitable habitat for *F. assa-foetida* within Kerman province. Under both Representative Concentration Pathway (RCP) scenarios examined, a severe reduction in suitable habitat area is projected, suggesting that current habitats face a high risk of near-total destruction in the future. This anticipated loss is driven by the synergistic effects of rising temperatures and altered precipitation regimes. Increasing temperatures exacerbate water stress, increase the frequency of extreme weather events and droughts, and reduce ecosystem resilience (Lioret *et al*., 2005). These changes can lead to reduced seed germination, diminished plant vitality, degradation of soil quality, and a subsequent decline in species survival, ultimately accelerating desertification. Furthermore, decreased humidity can increase the incidence of natural fires and pest outbreaks, further degrading natural ecosystems (Mengat *et al*., 2018).

Our findings are consistent with a growing body of research on the impacts of climate change on plant distributions. For example, Shi *et al*. (2022) projected a sharp decline in the potential habitat of *Meconopsis punicea* by 2050 and 2070. Similarly, Khajoei Nasab *et al*. (2022) predicted a loss of 70.51% to 90.01% of suitable habitat for the medicinal plant *Echium amoenum* under different RCP scenarios and timeframes. Naghipour *et al*. (2019) also forecasted significant reductions (19.7% to 61%) in the habitat of *Fritillaria imperialis* in central Zagros. These consistent results, further corroborated by studies such as Ghahsareh Ardestani *et al*. (2024) and Zhang *et al*. (2021), highlight the severe threat that climate change poses to biodiversity and the distribution of specialist plant species in arid and semi-arid regions. In conclusion, while the Maxent model demonstrates high accuracy in identifying the current ecological niche of *F. assa-foetida*, its future projections paint a concerning picture. The strong dependence of this species on specific temperature parameters makes it particularly vulnerable to global warming, portending a significant contraction of its suitable habitat in the coming decades.

## 5. Conclusion

Based on the findings of this study, it can be concluded that future climate change poses a severe threat to the survival of *F. assa-foetida*, a medicinally and economically important plant. Our models project a significant contraction in its climatically suitable habitat, potentially limiting it to a fraction of its current distribution and placing the species at a high risk of extinction. To mitigate this threat, a multi-faceted conservation strategy is imperative. The primary and most urgent measure is the stringent protection of its native habitat, including controlling anthropogenic habitat destruction and preventing the conversion of rangelands. While these actions cannot fully negate the impacts of climate change, they may bolster the species' resilience, allowing its inherent adaptations a greater opportunity to facilitate survival.

The prediction maps generated in this study provide a critical tool for natural resource managers, particularly in Kerman Province, to prioritize conservation areas, assess potential for resilience, and implement both current and long-term monitoring programs. Ultimately, these proactive steps are essential for preventing the extinction of this valuable species.

## Authors Contributions

All authors contributed equally to the conceptualization of the article and writing of the original and subsequent drafts.

## Data Availability Statement

Data available on request from the authors.

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## Ethical considerations

The author avoided data fabrication and falsification.

## Funding

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## Conflict of Interests

The author declares no conflict of interest.

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