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Potential extinction risk of *Juniperus phoenicea* under global climate change: Towards conservation planning

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A R T I C L E I N F O

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A B S T R A C T

Global change effects on species are most pronounced when there is a large mismatch between past climate conditions, and the present climate, and this chasm will grow as global change proceeds without mitigation. Global change encompasses the alteration of temperature and precipitation patterns worldwide and these drivers can both increase the risk of species extirpation, and extinction. Juniperus phoenicea is an endemic plant species in the Mediterranean region of high conservation concern. Ensemble distribution models and the potential impact of future climate scenarios revealed that temperature, isothermality, and precipitation are the only significant bioclimatic factors affecting the geographical distribution of J. phoenicea. To study the potential impact of global change, we constrained the SDMs with a combination of two shared socio-economic pathways (SSPs) climate scenarios in the near (2030) and far (2090) future, together with two dispersal scenarios (full and limited). After removing incompatible regions based on current land-use distribution, the comparison of the current and future areas of occupancy revealed strong declines in the distribution of J. phoenicea. Applying the IUCN criteria, the species is predicted in all scenarios to be up-listed from the currently "least-concern" status to the "vulnerable", and potentially to the "critically endangered" status under the highest emission scenario in 2090. The range shifts predicted by our analysis draws attention to regions with stable distribution, and others predicted to become favorable for the species establishment. This information is essential for future conservation planning, including afforestation and reforestation programs.

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1. Introduction

Accelerating climate change has the potential to alter plant species distributions and to increase the threatened status of many plant species. There is a critical need for predictive species distributions under future climate scenarios. Particularly, for areas that have been greatly modified by human activity and are thus more susceptible to the impacts of the global changes (Thompson, 2006; Otto et al., 2012). In the Mediterranean region, the threatened species are projected face decline in distribution and range shrinkage due to their sensitivity to the climate changes (Fontaine et al., 2007; Casazza et al., 2014; Karavani et al., 2018), particularly high-mountain endemic species (Mendoza-Fernández et al., 2022). Arguably, threatened species inhabiting arid coastal zones are most probably to be influenced by climate change because of their specific bioclimatic and topographical requirements (Palomo, 2017; Xu et al., 2019). One of the seriously affected species in the arid ecosystems of the Mediterranean region is the Phoenicean juniper (Picchi, 2008; El-Bana et al., 2010; Arar et al., 2020; Farahat, 2020). Juniperus phoenicea L. is a conifer that belongs to family Cupressaceae (Boulos, 1999).

Some species may undergo range shift as a compensatory mechanism to climate change by changing their geographic distribution to more climatically suitable regions (Bellard et al., 2012). The ecological tolerance of species and how they respond to climate change will determine how many species will be lost in a region (Guo et al., 2018; Urban, 2015). Several studies revealed that threatened plant species have already experienced reductions in range size, latitudinal shifts northward or altitudinal shifts to higher elevation in response to climate change (e.g., Hulin et al., 2009; McGuire et al., 2016; Arar et al., 2020). Yet, few studies have looked into how the distribution of the endemic threatened plant species in the Mediterranean environments will respond to the climate changes (Tabet et al., 2018; Arar et al., 2019; Bouahmed et al., 2019).

Mediterranean environments are characterized by high level of endemism and unique taxonomic composition (Mittermeier et al., 2005). Therefore, the Mediterranean region is deemed one of the main global biodiversity hotspots that are particularly threatened by anthropogenic pressures and climate change (Myers et al., 2000; Véla and Benhouhou, 2007). The region supports fragile ecosystems that are exposed to a combination of natural threats including droughts and soil erosion, as well as to human activities such as human-induced forest fires, deforestation, land use changes, expansion in urban development and agriculture activities for food and wood production (Barbero et al., 1990; Allen, 2001; Arar and Chenchouni, 2014; Arar et al., 2020). Juniperus phoenicea is one of the examples of Mediterranean species facing considerable threat from habitat degradation and might be vulnerable to climate change (e.g., Quercus Aegilops (Khwarahm, 2020); and Pistacia khinjuk (HamadAmin and Khwarahm, 2023)). This species is a small monoecious evergreen coniferous tree (Boulos, 1999). Its range extends from the Canary Islands and Madeira in the west to the North African Mediterranean countries and stretches to the Arabian Red Sea coast in the east (Farjon and Filer, 2013; Farjon, 2017), https://www.catalogueoflife.org/data/taxon/6NFYQ) and can inhabit areas characterized by arid conditions and high temperature (El-Bana et al., 2010). The overutilization of the species has contributed to the decline of the species (Moustafa et al., 2016). In some areas of its native range the species is under pressure from human activities, including the use of the wood and leaves for medicinal (Amer et al., 1994; Qnais et al., 2005; Mazari et al., 2010) and other purposes as fuelwood and ornamental plant in landscaping (Loureiro et al., 2007), as well as from frequent drought cycles, particularly in the arid and semi-arid ecosystems (Kabiel et al., 2016). Moreover, J. phoenicea is characterized by biological characteristics that may exacerbate the severity of the threatening effects. As a gymnosperm it has a slow reproductive cycle that exceeds 20 months (Arista et al., 2017). In addition, it has low seed production, germination rate, and reduced pollen viability (Ortiz et al., 1998). Climate change and the difficulty of J. phoenicea reproduction by seeds could drive many populations of this species to extinction. Additionally, global warming is expected to shift its geographic range. Predicting the potential distribution of J. phoenicea at the global scale using bioclimatic variables (e.g., Salvà-Catarineu et al., 2021), and at the local scale using bioclimatic and edaphic variables (e.g., Arar et al., 2020) raised the concerns regarding the need for the conservation of this species in dry mountainous region; particularly in Sinai, the Red Sea, and Saudi Arabia. The low dispersal and regeneration capability of J. phoenicea have been indicated as a main concern for the conservation prioritization of the species (El-Bana et al., 2010; Farahat, 2020; Quevedo et al., 2007; Salvà-Catarineu et al., 2021).

Species Distribution Models (SDMs) are based on the correlative relationship between the environmental factors and species presence (Elith and Leathwick, 2009) and can be used to predict potential species distributions under different climate scenarios (Araújo and Peterson, 2012). Therefore, SDMs have been employed as a tool for the evaluation of the impact of climate change on the geographic distribution of endangered species (e.g.,Thomas et al., 2004; Abrha et al., 2018; Arar et al., 2020). Commonly used correlative SDMs approaches that focus only on the depiction of species' bioclimate envelope for predicting the potential impacts of climate change on species distribution have been criticized for overlooking biophysiological factors (Gardner et al., 2019) and other bio-ecological variables that may influence species distribution (Pearson and Dawson, 2003; Elith and Leathwick, 2009). Particularly, biotic interactions, species potential evolutionary change, adaptive response to the changes in the environment, and dispersal ability (Pearson and Dawson, 2003; Sinclair et al., 2010; Thuiller et al., 2013). Reducing the uncertainty in SDMs for not considering the bio-ecological factors can be accomplished by using species occurrence based on systematic data collections, continuous monitoring for validation of models' outcomes (Elith and Leathwick, 2009; Sofaer et al., 2019), in addition to selection of appropriate set ecological predictors (Barbet-Massin and Jetz, 2014), climate scenarios and modelling algorithms (Van Echelpoel et al., 2015).

The use of different modeling algorithms in an ensemble model has been recommended as superior in terms of performance and transferability to the use of a single standard model (Guisan et al., 2017; Thuiller et al., 2019). The ensemble modelling approach was also recommended particularly for the evaluation of the climate change impact on species distributions and range shifts, over relying on the outcomes of a single modelling technique (Ahmadi et al., 2019; Della Rocca et al., 2019; Elith et al., 2010).

Climate change is considered among the main threats for Juniperus species (Rumeu Ruiz et al., 2011; Thomas, 2011; Wingate et al., 2011; MacLaren, 2016; Seim et al., 2016; Shaheen et al., 2017; Dakhil et al., 2021). Optimally, for species to track climate shifts, they should not be limited by geographical barriers or by dispersal limitation. This is unlikely to be the case for many species, J. phoenicea included. As a result, dispersal limitation is a critical aspect to consider to enhance the accuracy of the projections of the threatened species future distribution (Abbass et al., 2022). Recent studies showed that a number of threatened species could expand in distribution in response to future climatic change (Liao et al., 2020), but these studies should be carefully interpreted as they could include unrealistic dispersal scenarios.

For precise conservation assessment of threatened species to determine their extinction risk under climate change, the use of SDMs that integrate the IUCN Red List criteria, with dispersal scenarios and land-use land cover (LULC) adjustments into consideration is highly recommended (Dakhil et al., 2021b; Thuiller et al., 2019). The Area of occupancy (AOO) is one of the IUCN Red List criteria of proper use as a measure for species extinction risk. It is a more accurate measure than the estimation of the range shift or of the changes in the extent of habitat suitability (IUCN, 2022). Moreover, in most of the previous studies concerning the potential distributions under climate change scenarios, the Representative Concentration Pathways (RCPs) were used as a set of four pathways (2.6, 4.5, 6.0, and 8.5) (Jubb et al., 2013) to describe the different levels of greenhouse gas emission and the additional radiative forcing that could appear in the future (Hausfather, 2019). Since the RCPs ignore socioeconomic factors, other pathways that consider human population, economic growth, education, or urbanization, have been developed. They are called Shared Socioeconomic Pathways (SSPs, e.g., low emission scenario SSP 126, or high emission scenario SSP 585; (Hausfather, 2019). Therefore, the current study sought to: 1) evaluate the probable impact of climate changes based on shared socio-economic pathways (SSPs) on projected habitat suitability and future distribution of J. phoenicea considering full and restricted dispersal scenarios; 2) assess the loss in the AOO to evaluate the potential risk of extinction, and (3) recognize the conservation priority areas based on the loss, persistence, or gain of the predicted suitable habitats. We expect that the outcomes from the current study to help provide deeper insights on J. phoenicea conservation status and guide in devising the proper conservation measures that could guarantee the future persistence of this endangered species.

2. Material and methods

2.1. Species distribution data

We compiled the occurrence records of J. phoenicea (n = 8220) from (1) the GBIF databases (GBIF, 2021), and (2) previous studies specifically from Moustafa et al. (2016) and Farahat (2020). We verified and filtered the occurrence points by removing duplicates, points outside the study area, or outlier locations (e.g., lakes and land-use structures) using the global map of land cover with spatial resolution of 1 Km^2 in ArcGIS 10.3 (ESRI, Redlands, CA, USA). This resulted in the elimination of 1058 occurrence records. Additionally, all records with missing environmental data were removed resulting in 7067 occurrence records that were used in the subsequent analysis.

2.2. Bioclimatic, elevation, and human influence data

Elevation data were based on a digital model acquired from the USGS Dataset (https://www.usgs.gov). The 19 current and future bioclimatic predictors (Supplementary Data, Table S1) were obtained from WorldClim (Fick and Hijmans, 2017). Two global climate models namely the BCC-CSM2-MR (Beijing Climate Centre-Climate System Modelling) and the IPSL-CM6A-LR (The Institut Pierre-Simon Laplace-Climate Modelling Centre) were obtained from the most recent sixth level of the Coupled Model Intercomparison Project (CMIP6) (https://www.worldclim.org/data/cmip6/cmip6_clim30s.html), to assess the effect of climate changes on the species distribution. Data representing ecological indicators including the aridity index (AI), the potential and actual evapotranspiration (PET & AET) were acquired at a resolution ~ 1 km (Trabucco and Zomer, 2019; Fisher et al., 2011) from the CGIAR-CSI Global database (www.cgiarcsi.org). Nine soil physical and chemical variables were acquired from the ISRIC-World Soil Information database at 0–2 m depth at 30 arc-seconds spatial resolution (Hengl et al., 2014). Raster layers representing the means of soil physical and chemical variables at the different soil depths were generated in the framework of ArcGIS 10.5 (ESRI, 2015). To include indicators on the human-induced stressors influencing the terrestrial ecosystems, the data of the Global Human Modification of Terrestrial Systems, which encompass 13 anthropic stressors including human settlement, agriculture, transportation, and infrastructures; were acquired from the NASA Socioeconomic Data and Applications Center (SEDAC) at 1 km^2 spatial resolution (Kennedy et al., 2020).

All the predictor layers were resampled within the framework of ArcGIS 10.5 (ESRI, 2015) to a resolution of $\sim 2 \times 2\ km^2$, as advised by IUCN to facilitate the AOO estimation (IUCN, 2022).

To avoid model overfitting, we carried out multicollinearity test. The highly correlated variables were identified based on the value of the variance inflation factor (VIF), which quantifies how strongly a variable can explain the other predictors. The VIF analysis was conducted using the VIFcor and VIFstep functions of the "usdm" package (Naimi, 2015) withing the framework of R 4.2.0 (Team, 2021). We excluded the variables with the VIF values > 5 and a correlation threshold of 0.75, resulting in 15 variables were used in the subsequent analysis (Supplementary Data, Table S1).

2.3. Ensemble model building

An ensemble modelling of three models, the generalized linear model (GLM), the boosted regression trees (BRT), and the random forests (RF) was established to model the distribution of J. phoenicea using 'sdm' and 'ensemble' functions of the 'sdm' package within the framework of R 4.2.0 (Naimi and Araújo, 2016). The utilized modeling algorithms are recognized for the high stability and transferability of their prediction relative to other models. We used 70% of the data for training data and 30% as testing data (Thuiller et al., 2019). The True Skill Statistic (TSS) was used to weigh the modeling algorithms in building the ensemble model. The recommended threshold rule of maximum training sensitivity plus specificity (MTSS) was utilized (Liu et al., 2016). The evaluation of the accuracy of the constructed models was based on the area under the receiver-operating characteristic curve (AUC) and the TSS accuracy measures (Guisan et al., 2017).

The quantitative maps (obtained by ensemble modelling) of the present and the projected habitat suitability were transformed to suitable/unsuitable binary maps, based on the MTSS threshold to visualize the changes in habitat. Then the suitability maps were adjusted by the global land cover the mosaic vegetation classes of the global land cover map at spatial resolution 1 Km^2 (Tuanmu and Jetz, 2014) to exclude the inappropriate areas such as urban and water bodies. The ensemble of the mean of the outcomes from two GCMs for the near future (2021–2040) and far future (2081–2100) of two shared socioeconomic scenarios pathways (low scenario: SSP126 and high scenario: 585) was generated. This method provides superior results to those obtained from a single model (Dakhil et al., 2021a; Wang and Chen, 2014). All methodological steps are shown in the flowchart (Fig. 1).

2.4. Extinction risk assessment under climate and dispersal scenarios

It has been recommended for conservation studies under climate change to consider the IUCN guidelines land use change, and dispersal scenarios (Dakhil et al., 2021b; IUCN, 2022) to provide an extensive approach for conservation assessment and sensible conservation planning. To overcome the possible errors generated by geometric uncertainty, downscaling process, and issues with grid orientation or origin, the area of occupancy (AOO) we used as a proper measure of extinction risk (IUCN, 2022; Keith et al., 2018; Meynard et al., 2019). The extent of occurrence (EOO) was estimated using the 'ConR' package within the framework of R 4.2.0 (Dauby et al., 2017). Then, the resulting EOO shapefile was used to crop the produced binary maps of both current and future to get the EOO's scenarios (adjusted and not adjusted). Since dispersal scenarios are an important aspect of conservation planning (Thuiller et al., 2019), the full and limited dispersal scenarios were applied. Under the limited dispersal, the predicted pixels that appeared in new areas in the future (gain) were regarded as unsuitable. Under full dispersal, no restriction to the dispersal capability of the species was assumed, so the pixels were kept as part of the future distribution, even if they were not suitable in the potential current range (Kaky and Gilbert, 2019a). The AOOs were calculated under different scenarios. The percentage of the relative loss in the forecasted AOOs was used as a measure to assess the species extinction risk categories according to the IUCN's Red List Criterion A3(c) as follow: loss $> 30\% =$ vulnerable (VU), loss $> 50\%=$ endangered (EN), loss $> 80\% =$ critically endangered (CE), and 100% loss = extinct (EX) (Kaky and Gilbert, 2019b).

3. Results

3.1. Model performance/habitat suitability response to predictors

The ensemble model used to predict the distribution of J. phoenicea attained high accuracy and demonstrated excellent performance with an average AUC and TSS higher than 0.95 and 0.85, respectively (Fig. 2). The value of the predictors' relative importance revealed higher contribution of the bioclimatic variables compared to the other variables in predicting the potential distribution of J. phoenicea. The key bioclimatic variables determining the distribution of J. phoenicea were primarily temperature-related (temperature seasonality, isothermality, and mean temperature of driest quarter, and the mean temperature of the wettest quarter) in addition to the precipitation of warmest quarter (Fig. 2). In response to temperature seasonality, the probability of occurrence of the conifer species showed sharp decline with an increase in the temperature seasonality (Fig. 2). J. phoenicea response showed narrow optimum range of variation in isothermality (35–45 °C) and the probability of its occurrence declined with an the increase in the mean temperature of wettest quarter beyond 15 °C. It's worth noting that the occupancy of the species showed steep decline above 25 °C of the mean temperature of driest quarter and the current optimum range is between 5 and 10 °C (Fig. 2). Precipitation of the warmest quarter was the main moisture-related variable influencing the species distribution, where the probability of its occurrence was boosted with the rise in the precipitation of the warmest quarter (Fig. 2); however it sharply declined with the increase in precipitation above 150 mm in the warm season.

3.2. Habitat suitability and AOO under climate scenarios

Potential habitat suitability under the current climate revealed several areas that were excluded after adjustment to the global land cover map; this was particularly the case in the North African region (Fig. 3). The potential suitable habitats or likelihood of existence of J. phoenicea is projected to decline, leading to reduction in AOO under the lowest emission scenario of SSP 2.6 by nearly 36% in 2030 and 47% in 2090 (Table 1 and Fig. 4). The loss in projected AOO of J. phoenicea is in the same order of magnitude for SSP 8.5 in 2030 (39%), but its long-term prediction is alarming with more than 80% loss in 2090 (Table 1 and Fig. 4D). Interestingly, the differences between the full and limited dispersal scenarios were not substantial, with 1.4% on average for SSP 2.6%, and 2.2% for SSP 8.5 (Table 1).

The projected distribution based on MTSS threshold revealed that the species is predicted to have stable areas: they are currently considered suitable, and will continue to be climatically suitable in the near and far future (Fig. 4). These regions should be considered as priority conservation areas. However, when considering the current extent of occurrence (EOO), the predicted future changes under the investigated scenarios uncover substantial losses in suitable habitats. This indicates that J. phoenicea populations will be at high risk, especially in the most extreme climate scenario (Fig. 4D).

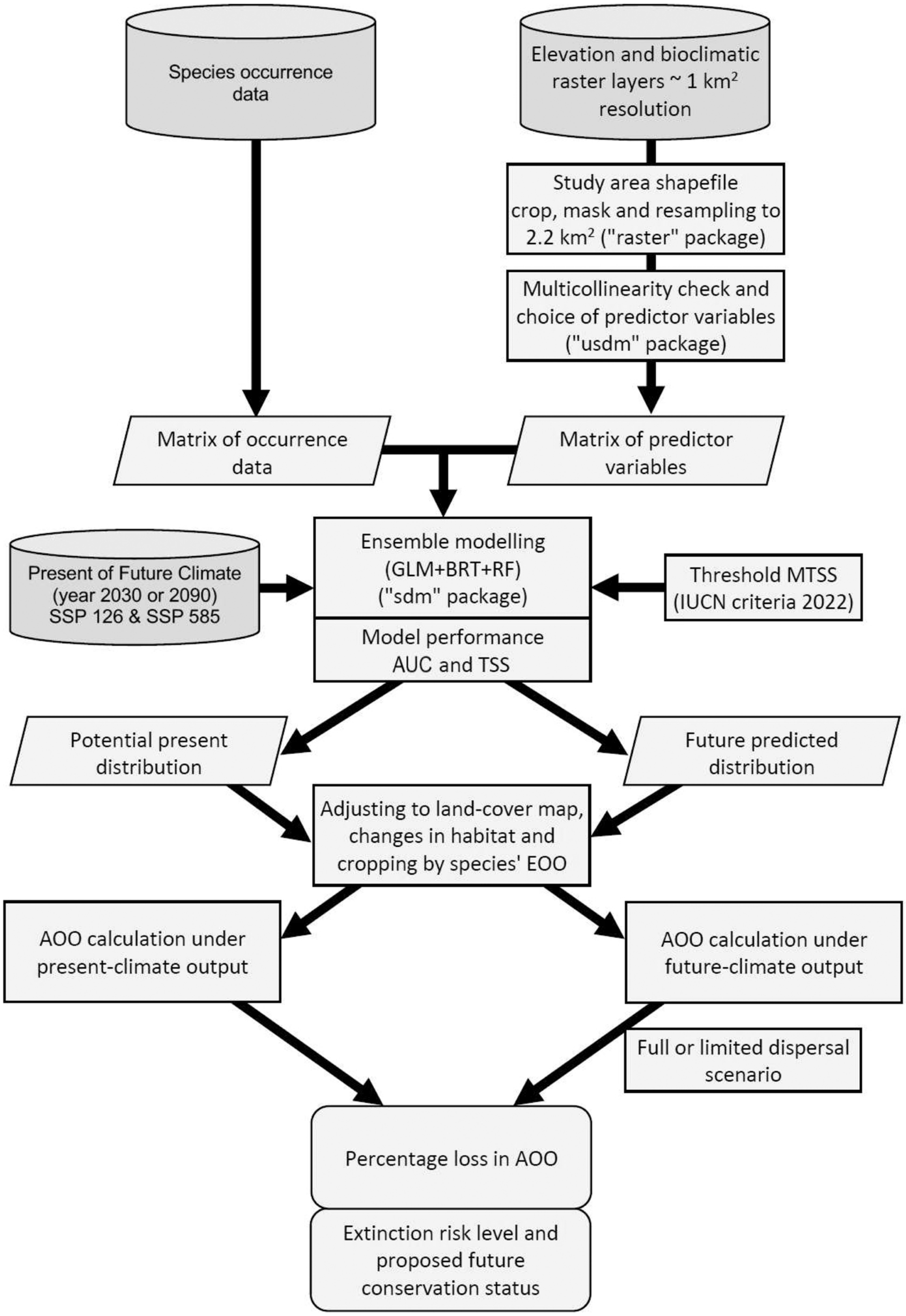

Fig. 1. Flowchart showing the spatial and statistical modelling analysis.
(modified from Dakhil et al., 2021b).

3.3. Extinction risk under dispersal and climate scenarios

The current IUCN conservation status of J. phoenicea is Least Concern. The status of J. phoenicea is projected to be assigned to higher extinction risk categories under all assessed climate and dispersal scenarios according to the expected loss in the percentage of AOO (IUCN Red List Criterion A3(C)). In particular, J. phoenicea is expected to be recognized as "vulnerable" under all the future scenarios, except the SSP 8.5 scenario, under which the species is expected to be identified as "critically endangered" by 2090 (Table 1).

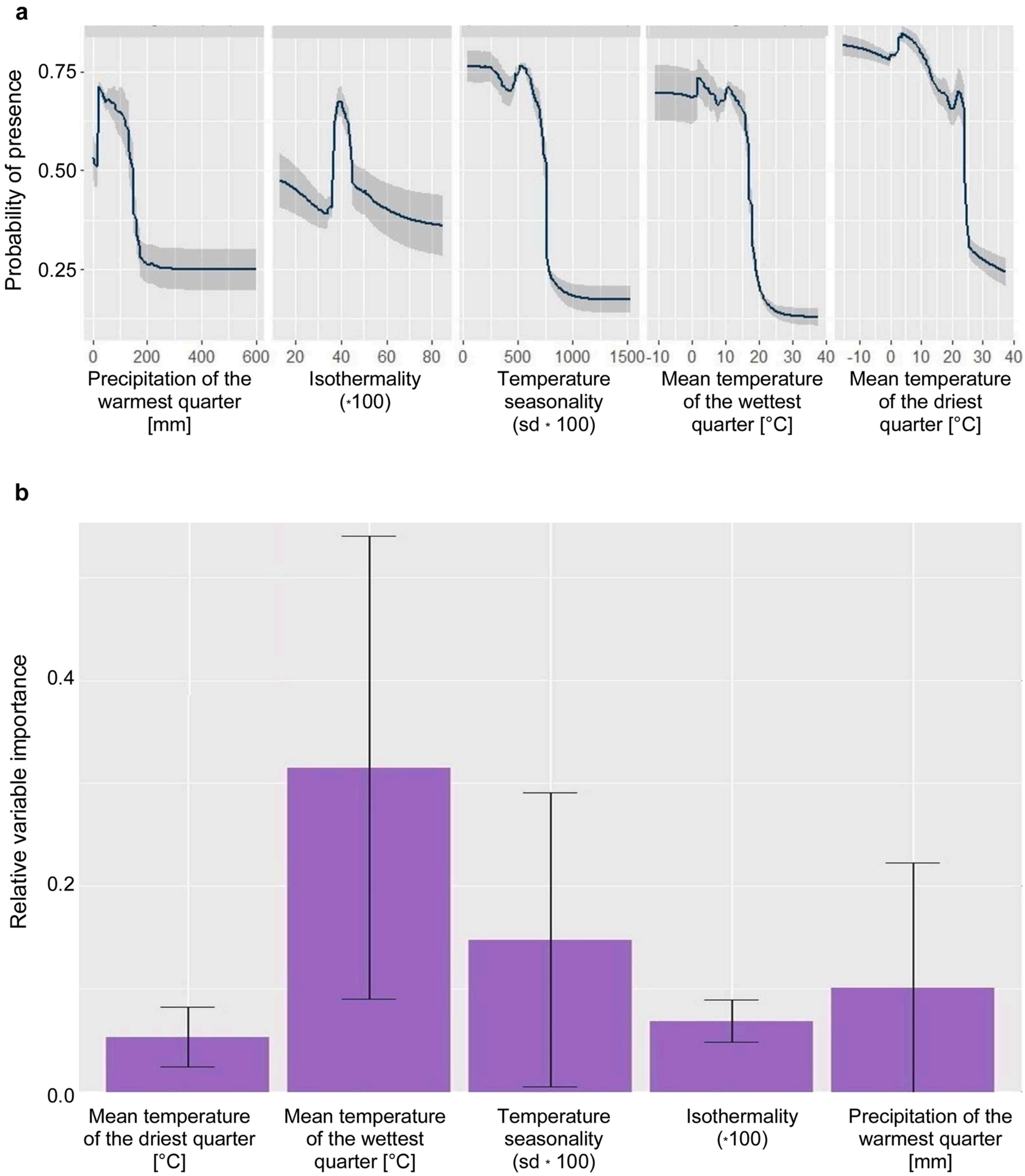

Fig. 2. (**a**) Response curves and (**b**) relative importance (average and 95% CI) of the bioclimatic predictors in modelling J. phoenicea potential distribution.

While all scenarios predict losses in the suitable habitats, gains are also projected under all scenarios, albeit very small compared to losses (Fig. 5). It is worth noticing that the maximum gain is expected under SSP 8.5 by 2030, while the minimum is under the same scenario by 2090. The gains are projected mainly in northern Spain, and central France. The potential losses of the suitable habitats of J. phoenicea were mostly projected in southern Europe and western Asia, particularly in central Spain, south France, south Italy, west and south of Greece, western and northern parts of Turkey, and north Morocco, Algeria and Tunisia (Fig. 4). Most of the stable areas are projected to be mostly located in Spain, western France and UK. A reduction of more than 50% in J. phoenicea stable areas is predicted under SSP 8.5 by 2090 relative to its predicted extent under SSP 2.6 by 2030. Areas that will experience losses could be assumed as

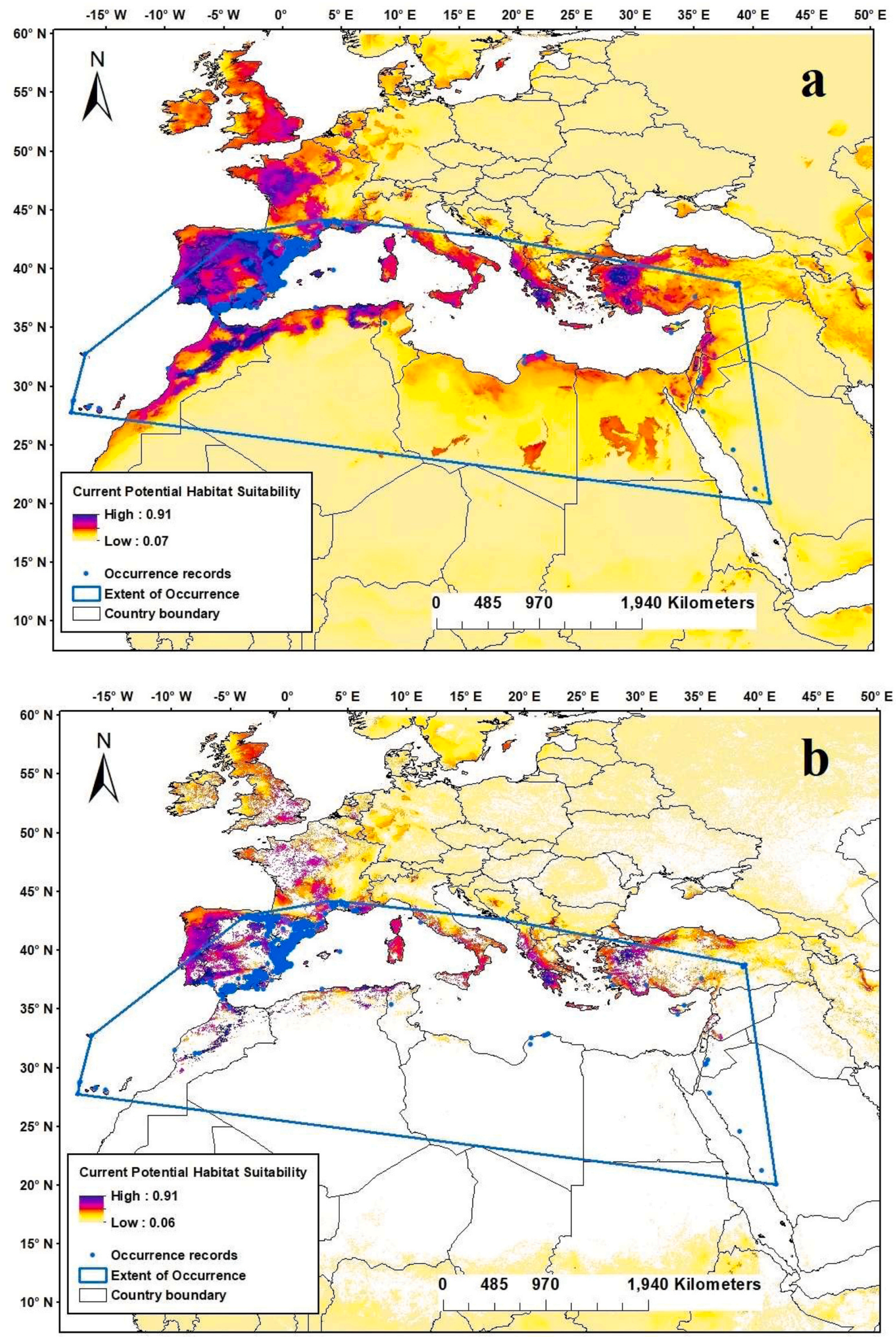

Fig. 3. Global distribution of Juniperus phoenicea and its potential habitat suitability under the current climate: (a) non-adjusted to global land cover map; (b) adjusted to global land cover map. The adjusted map is used for comparison with the future-scenarios maps in Fig. 4. Proposition: **Current** extent of occurrence: only a thick blue line; Country boundary: only a thin black line; The white rectangle becomes "Unsuitable according to global land cover map.

Table 1
Percentage of loss in the area of occupancy (AOO) of J. phoenicea under the four climate change scenarios and the two dispersal scenarios. The proposed IUCN conservation status or extinction risk is included (VU=Vulnerable; CR= Critically endangered), with the current status being 'Least Concern'.

Climate Change Scenario	AOO Loss %		Proposed IUCN status*
	Full dispersal	Limited dispersal	
SSP 2.6 (2030)	35.74%	36.79%	VU
SSP 2.6 (2090)	46.08%	47.78%	VU
SSP 8.5 (2030)	38.20%	40.22%	VU
SSP 8.5 (2090)	80.68%	83.03%	CR

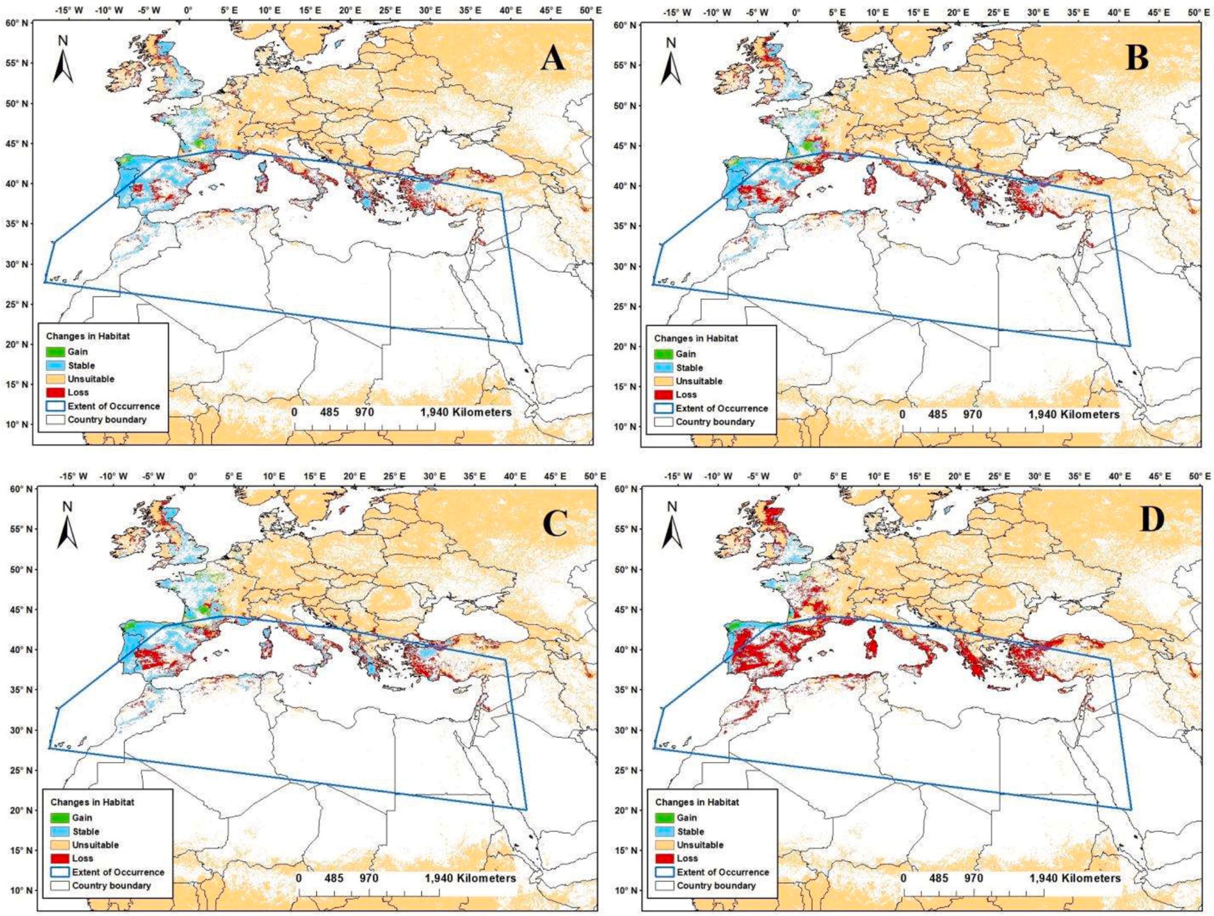

Fig. 4. Potential changes in habitat using the threshold MTSS = 0.37 (Maximum training sensitivity plus specificity) under the future climate scenarios: (A) SSP26 (2030); (B) SSP26 (2090); (C) SSP85 (2030); (D) SSP85 (2090).

priority conservation areas of the threatened conifer species, while the stable areas could be considered for ex-situ conservation and establishing of proposed nature reserves.

4. Discussion

4.1. Potential distribution and contributing factors

The current study offers an assessment on the vulnerability of J. phoenicea and its potential loss in suitable habitat due to future climate change and the implications for the conservation status of the species. The ensemble model employed in the study generated robust distribution models as was indicated through the evaluation based on the plausible measures of model performance. The used modelling approach reported to produce has been robust prediction of species distribution in relevant studies (e.g., Dakhil et al., 2021a, 2021b; Della Rocca et al., 2019). Also, the integration of two GCM climate models (BCC-CSM2-MR and MIROC6) in the current

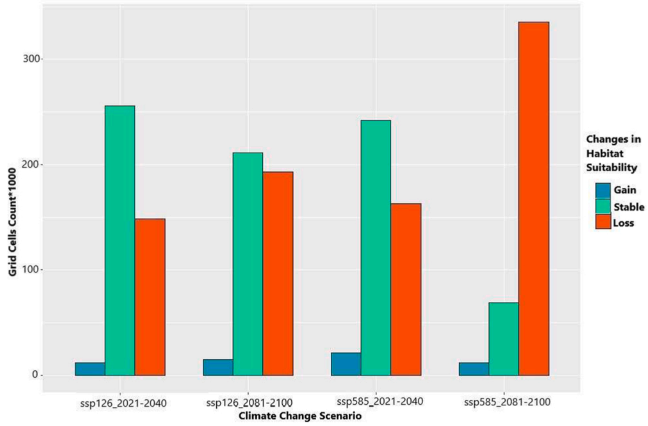

Fig. 5. Changes in potential habitat (gain, stable and loss) based on the number of grid cells (size of $2 \times 2\ m^2 \times 1000$) under the four future climate scenarios.

study should improve the predictability of species distribution models and projections. The use of the average of the ensemble of climate scenarios helps to minimize the uncertainty in SDM outputs by taking into account the discrepancies among alternate scenarios of future climate (Beaumont et al., 2008).

The relative importance of the predictors used in modeling J. phoenicea distribution varied noticeably. The temperature-related variables, particularly the mean temperature of wettest quarter, temperature isothermality, seasonality, and mean temperature of driest quarter were the key factors shaping J. phoenicea distribution in its current range. Consistently, other studies reported that temperature seasonality and mean temperature of driest quarter are among the most important ecological drivers influencing the distribution of J. phoenicea (Arar et al., 2020; Dakhil et al., 2022; Salvà-Catarineu et al., 2021). Although the species is adapted to the Mediterranean climate with dry and hot summers (Adams et al., 2013; Mazur et al., 2016); it is sensitive to temperature variation and its occurrence is correlated with low annual temperature variability. Therefore, projections based on the rise in temperature seasonality forecast considerable reduction in the climatically suitable areas for J. phoenicea. The rise in temperatures during the driest quarter heightens drought and influences J. phoenicea occurrence (Baquedano and Castillo, 2007; Lloret and Granzow-de la Cerda, 2013). It has been reported that J. phoenicea suffered severe defoliation and seedling mortality due to increase in drought incidence (De Dato et al., 2009). The rise in temperature was associated with an increase in J. phoenicea seed predation and contributed to lower seedling recruitment (Mezquida et al., 2016).

Despite the perception that conifers in high mountainous region are fairly insensitive to precipitation variability (Wang et al., 2017), our results revealed that moisture-related variables, particularly precipitation of warmest quarter, were determining factors of the J. phoenicea distribution. Decline in precipitation in spring and summer will increase aridity, which was reported to raise mortality rates of Juniper tree in the Mediterranean region (Elmahdy and Mohamed, 2016; Lloret and Granzow-de la Cerda, 2013; Salvà-Catarineu et al., 2021; Walas et al., 2019; Wang et al., 2017).

Studies have reported that the growth of the conifers dwelling higher elevations are restricted by temperature, while those inhabiting the lower altitudes are constrained by moisture availability (Salzer et al., 2009). Further investigations are needed to explore the physiological mechanisms that will regulate the species' response to climatic changes. Global warming might increase the magnitude and incidence of extreme droughts in the Mediterranean Basin, which could endanger many plant species (Lange, 2020), J. phoenicea included. Studies have revealed that tree species with shallow root systems were the most negatively affected by incidence of drought (Gazol et al., 2017). J. phoenicea has a shallow root system relative to angiosperm species with similar lifeform, therefore it is expected to suffer more from the consequences of drought.

4.2. Climate change effect on suitable habitat and AOO

The change in the AOO has been used as a robust indicator of extinction risks (e.g., Ahmadi et al., 2019; Kass et al., 2021). As revealed from the ensemble model outcomes, the probable changes in habitat suitability or AOO followed the similar trend under the SSP 2.6 and SSP 8.5 emissions scenarios, and the full and restricted dispersal assumptions. Over 30% of the climatically suitable habitat is projected to be lost by 2030 under both emissions scenarios assuming full and restricted dispersal. The shrinkage in the suitable habitat is likely to grow by 2090. Other SDMs-based projections of Juniperus species worldwide have reported habitat contraction and a tendency for northwards shift under future climate scenarios (e.g., Arar et al., 2020; Salvà-Catarineu et al., 2021; Naghipour et al., 2021).

The climate scenarios projected more loss in the eastern, the central and southern parts of the current extent of occurrence, while the gains are projected in the northern and western areas. This indicates that J. phoenicea is expected to exhibit a latitudinal and longitudinal shift from its current distribution range as a response to the changes in climate that will lead to changes in the AOO and EOO of the species. Under a harsher climate, species could respond through rapid acclimatization, slow adaptation, and altitudinal and latitudinal shifts (Barredo et al., 2016). Other studies conducted at different scales projected northward shift in the species range (e.g., Arar et al., 2020; Salvà-Catarineu et al., 2021). The models revealed persistent habitats of J. phoenicea that will continue to support the existence of the species under all combinations of climate and dispersal scenarios. These areas predicted to remain stable habitat for the species likely represent spots where the species will undergo a local altitudinal shift. Other studies have reported potential of altitudinal shift of the species (e.g., Arar et al., 2020). Species are predicted to react differently under the diverse climate change scenarios (Fei et al., 2017). Extreme temperatures tend to challenge the survival limits of each species differently, and this could be translated into low growth rates in the most extreme scenarios, which could eventually lead to local extinction (Agudelo-Hz et al., 2019; Selwood et al., 2015). The trees of J. phoenicea were observed to undergo dying out over the last decade (Arar et al., 2020; Kabiel et al., 2016).

The climate scenarios assuming limited dispersal projected slightly greater loss in AOO compared full dispersal scenarios. The dispersal of plant species is markedly constrained by the availability suitable habitat as well as the connectivity among available habitat patches (Guo et al., 2018), which can be adversely affected by land-use changes. Extent of suitable habitat and the AOO are deemed as spatial attributes that capture the collective effects of climate change with those resulting from the habitat loss due to land use/cover changes (Agudelo-Hz et al., 2019). However, the approach employed in the current study based on SSP climate scenarios did not account for the potential impact of the future changes in the land use/land cover, or the influence of other human activities such as grazing and fuelwood collection, which could cause fragmentation and pose significant threat to the species (Dakhil et al., 2022; Farahat, 2020; Kabiel et al., 2016; Quevedo et al., 2007). The probable combined influence of the land-use changes under the investigated climate change scenarios might exacerbate the risks to the species and calls for more investigations on these human-induced impacts.

4.3. Potential risks and conservation implications

J. phoenicea has been evaluated for The IUCN Red List of Threatened Species in 2016 and based on this assessment the species has been listed as Least Concern (Allen, 2017). The expected loss in the AOO-IUCN Red List Criterion A3 (C)-under all combinations of climate and dispersal scenarios revealed that the future conservation status of J. phoenicea to be up-listed to higher extinction risk category of vulnerable (VU). The risk category will be even up-listed to critically endangered (CR) under SSP 8.5 scenarios by 2090). Other drivers could of course increase the risks imposed on this species, for example land-use changes, fires, overexploitation (Moustafa et al., 2016), or invasive species.

The predicted effect of climate change on J. phoenicea ought to be incorporated in the conservation actions and management efforts, which should prioritize areas detected as persistent habitats when designing reserve areas and for any other appropriate conservation measures. In particular, those areas located in Spain, western France and UK, ought to be prioritized for ex-situ conservation and for establishing future protected areas. For regions predicted to gain suitable habitats under all the scenarios (e.g., northern Spain, and central France), connectivity to current suitable habitat needs to be maintained. Areas in southern Europe and western Asia where scenarios projected potential losses of the suitable habitats might consider plantations in botanical gardens and arboreta to maintain the genetic diversity of this species. Also, decisive action and strategies are needed to improve local populations awareness of the impact of anthropic activities on potential extinctions of J. phoenicea. However, the assessed changes in AOO accounted for the current distribution of land cover, no consideration was given for the future scenarios of land use changes and the associated consequences on the AOO. Future land transformation in J. phoenicea EOO might divide and disaggregate the suitable habitats into isolated patches, thus reducing habitat connectivity and negatively influence the species dispersal capability. Future assessment of the combined impact of climate and land use changes on suitable habitat availability, fragmentation, connectivity, and the capability J. phoenicea dispersal are recommended. Accounting for the combined impact of future climate change and land transformation on habitat availability, fragmentation and connectivity is crucial for successful conservation efforts (Krosby et al., 2010). Therefore, the development of management policies for J. phoenicea should give full consideration to the synergistic effects of climatic and land-use changes.

Finally, the ensemble approaches utilized in this study effectively addressed uncertainties and discrepancies associated with single model outputs, leading to more reliable projections applicable to general species management and conservation actions. Integration of information from two GCM climate models further enhanced the reliability of these projections (Beaumont et al., 2008). While these outcomes can inform general species management decisions, continuous validation through monitoring and field observation is necessary to improve their reliability for decision-making regarding species priority conservation (Sofaer et al., 2019). It is important to note that bioclimatic variables, although important predictors of species potential distributions, they do not encompass the full range of ecological factors influencing species occurrence. Furthermore, static modeling approaches may not fully capture species' evolutionary and adaptive responses to changing environmental conditions. To enhance ecological reliability, it is crucial to integrate other data sources, including expert knowledge, into the modeling process (Van Echelpoel et al., 2015). Furthermore, it is crucial to highlight alternative model accuracy measures, such as similarity/F-measure metrics (Leroy et al., 2018; Jiménez-Valverde, 2014), which are not influenced by species prevalence and can therefore enhance modeling performance. Consideration of limitations in spatial scale and future land use scenarios is also necessary in integrative modeling approaches to assess the combined impact of climate and land use changes on suitable habitats for J. phoenicea. This information can guide general conservation planning by addressing habitat fragmentation, connectivity, and species dispersal capabilities.

5. Conclusion

Combining state-of-the-art modelling methods and different climatic and dispersal scenarios, our results consistently revealed that projected loss in AOO will be substantial, resulting in an up-listing of the conservation status of J. phoenicea from least-concern to vulnerable and even critically endangered. The species is projected to undergo latitudinal and longitudinal shifts in response to the changes in climate. Conservation efforts and prioritization ought to be dedicated to the establishment of nature reserves, firstly in the stable spots predicted to remain climatically suitable for the species, and secondly in ex-situ suitable areas. The comparison of the current and predicted maps of habitat suitability provided in our contribution will serve as a decisive tool, as they allow to delineate the most promising regions for the establishment of both types of measures. The outcomes of the study can guide managers and relevant decision makers and experts, to implement efficient afforestation and reforestation programs.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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CRediT authorship contribution statement

RFE and MAD conceived the approach with substantial contributions from LFB and MC. RFE and MAD collected the data sets and carried out the statistical and modelling analyses. RFE, MWH and MAD wrote the first draft with substantial contributions of LFB and MC. AE, EF, MWH, SD helped with the writing of the manuscript. All authors gave final approval for publication.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request. The datasets generated during the current study are available from the corresponding author on reasonable request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2023.e02541.

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