In-situ and ex-situ conservation priorities and distribution of lentil wild relatives under climate change: A modelling approach

Salma Rouichi[1] | Michel Edmond Ghanem[1,2,3] | Moez Amri[1]

[1]AgroBioSciences Program (AgBS), College of Agriculture and Environmental Science (CAES), Mohammed VI Polytechnic University (UM6P), Ben Guerir, Morocco

[2]Centre de coopération internationale en recherche agronomique pour le développement (CIRAD), AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

[3]UMR AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

Correspondence
Moez Amri
Email: moez.amri@um6p.ma

Abstract

1. Lentil wild relatives are an important source of desirable traits that can be used for improving the productivity and resilience of cultivated lentil. Yet, our understanding of their habitat suitability and associated environmental factors remains limited. This study aimed to (i) assess climate change's impact on the potential distribution of six wild lentil species (*Lens culinaris* subsp. *orientalis*, *L. culinaris* subsp. *tomentosus*, *L. culinaris* subsp. *odemensis*, *Lens ervoides*, *Lens lamotte* and *Lens nigricans*) under various climate scenarios and (ii) assess their risk of extinction and determine their in-situ and ex-situ conservation status.

2. We used a species distribution modelling approach with MaxEnt to assess the present and future potential distribution of wild lentil species. Extinction risk was evaluated based on International Union of Conservation of Nature criterion B, and the conservation status was assessed using the GapAnalysis method.

3. The precipitation of the coldest quarter (bio19) and the minimum temperature of the coldest month (bio6) were found as the most important variables influencing the distribution of wild lentil species. Final Conservation Score (FC$_S$) ranged from 17.85 and 37.55, highlighting three wild lentil species (*L. ervoides*, *L. nigricans*, and *L. culinaris* subsp. *tomentosus*) with high priority for conservation and medium priority for the remaining species. *L. culinaris* subsp. *tomentosus* is categorized as a vulnerable species, while the other five species are of least concern or near threatened.

4. *Synthesis and applications*: This study underscores the urgent need for policy development to safeguard the diversity of lentil wild relatives in the face of climate change. The identified vulnerability of *Lens culinaris* subsp. *tomentosus*, among others, needs prompt and proactive conservation actions. Key management practices include the establishment and expansion of protected areas, habitat restoration, and the promotion of sustainable land use practices. The integration of effective in-situ and ex-situ conservation strategies, along with ecological

---

Michel Edmond Ghanem and Moez Amri contributed equally.

management practices, is essential. These measures, not only, enhance biodiversity conservation but also improve the resilience of agricultural ecosystems. Such an approach is pivotal in shaping effective conservation management practices for lentil wild relatives, promoting a sustainable agricultural system and ensuring food security in an evolving climate scenario.

1 | INTRODUCTION

Crop wild relatives (CWRs) are wild plant taxa genetically related to cultivated crops, possessing favourable traits transferable to cultivated species (Guarino & Lobell, 2011). These species have gained significant importance in the context of climate change as they provide genetic resources for mining adaptive traits (Heywood et al., 2007). Their distribution across diverse habitats and environmental conditions establishes them as valuable reservoirs of genetic diversity and they constitute major contributors to sustainable agriculture and food security (Coyne et al., 2020; Mammadov et al., 2018; Maxted & Kell, 2009; Phillips, Magos Brehm, et al., 2017). Mishra et al. (2023), in their FAO report, emphasizes the importance of CWRs in adapting agricultural practices to climate change. It advocates for exploration, collection, conservation and maintenance of germplasm. This is crucial for developing new cultivars capable of thriving in varied agroecological environments. However, CWRs are under increasing threat from habitat loss, urbanization, overharvesting, climate change and more. Climate change effects, such as altered precipitation patterns and increased extreme weather events, can impact species' population dynamics and habitat suitability. Furthermore, some species may not adapt to the shifting climate niche, leading to migration to more suitable climates or, if not possible, population decline or extinction (Bellard et al., 2012; Costa-Pinto et al., 2024). These pressures not only alter the distribution of CWR populations but also erode their genetic diversity, posing challenges to their conservation and potential utility (Castañeda-Álvarez et al., 2016; Guarino et al., 2002; Jarvis et al., 2008).

Ensuring the conservation and sustainable use of CWRs is crucial to ensure food security and agricultural sustainability. Initial assessments of genebanks' collections revealed substantial gaps in the comprehensiveness of the conservation efforts of CWRs (Vincent et al., 2013). Studies conducted by Castañeda-Álvarez et al. (2016) and Khoury et al. (2019), highlight the lack of geographic and ecological representation of CWRs in genebanks for a large number of taxa associated with numerous crops. Castañeda-Álvarez et al. (2016) identified 313 taxa representing 63 crops that lack available germplasm accessions and 257 taxa having less than 10 accessions. More than 70% of these taxa are considered high priority for conservation, and over 95% are inadequately represented in terms of their full geographic and ecological range of variation in their native habitats. In their investigation (Zair et al., 2021) CWRs related to 61 different crops, including lentils, revealed a comprehensive lack of adequate representation within genebanks across all crop gene pools examined. This finding underscores the imperative for enhanced efforts in the collection and preservation of genetic materials to ensure the biodiversity of essential crops is comprehensively safeguarded.

Lentil (*Lens culinaris* Medik.) is one of the oldest domesticated crops, with evidence tracing back its domestication with the beginning of agriculture at the Fertile Crescent from where it has subsequently spread throughout the Mediterranean region, North Africa, and to a lesser extent, Southern Europe. Over the years, the classification of the *Lens* genus has undergone many revisions based on morphological characteristics, geographic distribution and genetic analysis (Smýkal et al., 2015). Presently, the *Lens* genus is classified into seven species, including one cultivated species *L. culinaris* Medik and six wild species and subspecies: *L. culinaris* subsp. *orientalis*, *L. culinaris* subsp. *tomentosus*, *L. culinaris* subsp. *odemensis*, *Lens lamottei*, *Lens ervoides* and *Lens nigricans* (Ferguson et al., 2000; Smýkal et al., 2015). Conserving lentil's CWRs through both in-situ and ex-situ strategies is crucial for the sustainability and advancement of lentil breeding. In situ conservation preserves these species in their natural habitats, maintaining their ecological roles and ongoing evolution, which is essential for capturing genetic adaptations to changing environments. Ex situ conservation involves safeguarding their genetic diversity in genebanks and seed repositories, providing a backup against habitat loss and ensuring access for future research and breeding. These wild relatives are indispensable in lentil breeding programs under climate change. They key source for mining desirable traits for disease resistance, drought and high temperature tolerance, and yield improvement and their introgression into the cultivated species and development of new varieties with enhanced resilience and better nutritional value and productivity (Coyne et al., 2020; Gorim & Vandenberg, 2018; Hamdi & Erskine, 1996; Khazaei et al., 2016).

The global conservation status of wild lentil species has received little attention, posing a major challenge to their utilization. Smýkal et al. (2015) showed that the lack of effort in conserving the diversity of legume wild relatives resulted partly from a disconnect between academic studies identifying where genetic reserves and conservation activities should be established and the actual implementation of these activities. In this context, the gap analysis methodology for species conservation is a process for identifying threatened species and prioritizing their conservation status and needs based on the gaps in current conservation efforts (Brum et al., 2017; Khoury et al., 2019, 2020). While previous research (Zair et al., 2021) has examined

conservation gaps in lentil CWRs in general, still a comprehensive assessment of the conservation status for each of the six lentil wild species is currently lacking. Boyraz Topaloğlu et al. (2023) recently analysed the gaps in the conservation of lentil CWRs. The approach, however, had several limitations, notably the omission of spatial autocorrelation between the records and the exclusion of data points sharing identical environmental variables. Furthermore, the study did not include *L. culinaris* subsp. *tomentosus*, an important wild relative of lentil, in their assessment. Additionally, the assessment was based solely on one data source.

In this study, we tried to address these questions and use a gap analysis methodology to assess the conservation status of the six wild lentil species. Our objectives were to (1) predict the current potential distributions of the six wild lentil species using MaxEnt "Maximum Entropy" (Phillips et al., 2004, 2006, 2009) and identify environmental variables potentially influencing their distribution range, (2) predict the potential distribution of these six wild lentil species under two climate change scenarios (SSP2-4.5 and SSP5-8.5) for 2050 and 2070, (3) evaluate the conservation status of each of these six wild lentil species to identify the extent of at-risk or insufficiently conserved diversity both ex-situ and in-situ and (4) conduct a preliminary risk of extinction assessment for the six wild lentil species based on International Union of Conservation of Nature (IUCN) criterion B.

2 | MATERIALS AND METHODS

2.1 | Study area

The study area was confined to the native distribution range of wild lentil species, spanning from latitude 20°36′ to 58°49′ N and longitude 16°43′ W to 86°39′ E (Figure 1). Previous research

(Coyne et al., 2020; Ferguson et al., 1998; Maxted et al., 2011; Singh et al., 2014) has suggested that the distribution of all wild lentil species intersects with the Fertile Crescent. Specifically, *L. culinaris* subsp. *orientalis* is mainly found in Syria, Lebanon, Palestine and Cyprus, with additional occurrences documented in Azerbaijan, Uzbekistan and Tajikistan. On the other hand, *L. culinaris* subsp. *odemensis* and *L. culinaris* subsp. *tomentosus* exhibit a limited distribution, primarily found in Syria, Palestine and Turkey. The distribution of *L. ervoides* extends from Syria and Jordan to Palestine and extends westwards to Italy and Croatia. Similarly, *L. nigricans* occurs in Syria and Turkey, then further westward in Italy, France, and Spain, while *L. lamottei* is restricted to Spain and France (Figure 1).

2.2 | Species occurrence data

Occurrences of the six *Lens* species were compiled from two primary sources: (i) the Global Biodiversity Information Facility (GBIF.org, 2022a, 2022b, 2022c, 2022d, 2022e, 2022f) which aggregates data from herbaria, botanic gardens and other plant repositories and (ii) Genesys (Virtual Genebank of Plant Genetic Resources for Food Agriculture, https://www.genesys-pgr.org/ , accessed on 22 September 2022). To ensure consistency, the World Checklist of Selected Plant Families was used to cross-check accession names with their current accepted names (WCSP, 2022). The obtained dataset for each species underwent several filtering steps using the 'dplyr' R package. Non-georeferenced records, duplicate, entries exhibiting null geographic coordinates (latitude and/or longitude), spatial outliers (data points beyond the predefined boundaries of the study area) and erroneous occurrences (records located in inland water bodies or the ocean) were
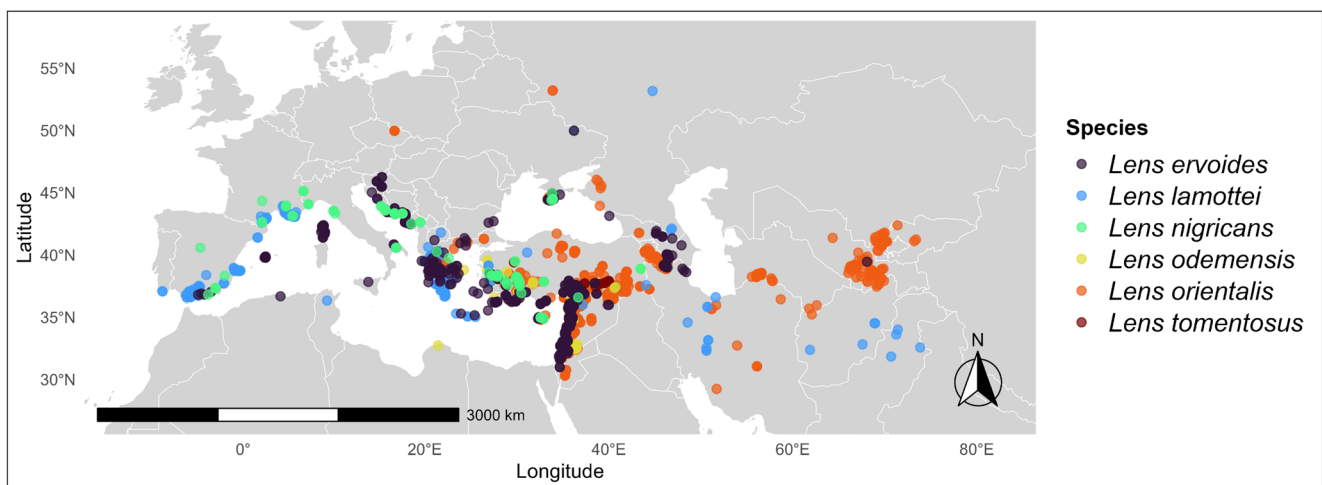

FIGURE 1 Map showing the distribution of the six wild lentil species (*Lens culinaris* subsp. *orientalis*, *L. culinaris* subsp. *tomentosus*, *L. culinaris* subsp. *odemensis*, *Lens lamottei*, *Lens ervoides* and *Lens nigricans*) in the study area, with each species marked in a different colour. The occurrence list, available in the Supplementary data (Rouichi et al., 2024a), provides the coordinates for each of the 1761 occurrences (Created using R).

removed. To address spatial autocorrelation between records and exclude data points with the same environmental variables, the dataset was thinned to a maximum of one occurrence per species per raster cell 2.5 of arcmin (~5 km) using the 'Spthin' package (Aiello-Lammens et al., 2015).

2.3 | Environmental variables

To model the current species distribution patterns of wild lentil species, 22 environmental factors that could potentially affect their distribution were used. These include 19 bioclimatic variables at a spatial resolution of 2.5 arcmin, obtained from the WorlClim 2.1 database (www.worldclim.org) (Fick & Hijmans, 2017), representing the average climatic data from 1970 to 2000. Additionally, a digital elevation model—obtained from the Shuttle Radar Topography Mission with a spatial resolution of 250 m—was used for the topographic characterization. Additional environmental variables from satellite remote-sensing products that have been widely used in ecological studies (Cavender-Bares et al., 2020) such as the Normalized Difference Vegetation Index and Leaf Area Index, were extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) using the NASA AppEEARS interface (https://appeears.earthdatacloud.nasa.gov) at a resolution of 250 m. All ecogeographic variables were resampled to a resolution of 2.5 arcmin and cropped within the study area using the R package 'raster'. To address the issue of spatial correlation among environmental variables (Porfirio et al., 2014) and minimize the risk of multicollinearity and model overfitting, the variance inflation factor (VIF) was applied to filter highly correlated variables. Using the R package 'usdm' (Naimi et al., 2014), the VIF was computed based on the correlation coefficients (R^2) derived from regressions between all variables. Variables with a VIF exceeding 10 were identified as significantly correlated to other variables, indicating multicollinearity (Yoon & Lee, 2021).

To predict the potential distribution of the six wild lentil species under future climate conditions, we considered the average outputs from sixth Global Circulation Models (GCMs): Beijing Climate Center Climate System Model version 2 (BCC-CSM2-MR), Centre National de Recherches Météorologiques Climate Model version 6.1 (CNRM-CM6-1), Canadian Earth System Model version 5 (CanESM5), Model for Interdisciplinary Research on Climate Earth System version 2 for Long-term simulations (MIROC-ES2L), Model for Interdisciplinary Research on Climate version 6 (MIROC6) and Meteorological Research Institute Earth System Model version 2.0 (MRI-ESM2-0). These models were used under two shared socio-economic pathways: SSP2-4.5 and SSP5-8.5 (Riahi et al., 2017). SSP2-4.5 represents an intermediate development pathway with a radiation forcing of 4.5 W/m^2 in 2100, while SSP5-8.5 represents the high end of the range of future pathways with a radiation forcing of 8.5 W/m^2 in 2100. These GCMs were used to predict the average suitable distribution areas over two time periods: 2050 (average for 2041–2060) and 2070 (average of 2061–2080).

2.4 | Model process

We used MaxEnt (Maximum Entropy) to simulate the present and future potential suitable areas for each of the six wild lentil species (Phillips et al., 2004, 2006; Phillips, Anderson, et al., 2017). MaxEnt is a machine learning algorithm that predicts the geographic distribution of a species using only data on where the species has been observed (presence-only data), without requiring information on where the species is absent. There are several review articles discussing the principles of MaxEnt calculations, as well as the influence of the input parameters on the simulation result (Elith et al., 2010, 2011; Guillera-Arroita et al., 2015; Merow et al., 2013). The methodology is based on the search for patterns in the distribution of environmental factors at locations of species occurrences. The input data comprise the geographical coordinates of the occurrence data points for a species and environmental factors (referred as predictors) that describe the spatial variability of environmental factors over the entire study area. Environmental factor values from both background and occurrence points are converted into predictive functions, termed features, for subsequent analytical use. These features undergo basic mathematical modifications from their original environmental factor values, including linear transformations (unmodified environmental factors, denoted as *L*), quadratic transformations (environmental factor values squared, denoted as *Q*), multiplicative interactions (product of pairs of environmental factors, denoted as *P*), binary thresholding (a binary representation of environmental factors, assigning 0 for values below a specific threshold and 1 for values above, denoted as *T*), and linear thresholding or hinge transformations (original environmental factor values maintained unless below a certain threshold, at which point they are adjusted to a constant value, denoted as *H*). The selection of features for analysis is contingent upon the count of occurrence points available: linear features are applied to datasets exceeding 10 points; linear and quadratic for datasets containing 10–15 points; linear, quadratic and hinge features are suitable for 15–80 points; and all types of features are recommended when the dataset encompasses more than 80 occurrence points. The R package 'ENMeval' was then used to test the Akaike information criterion (AICc) correction (Muscarella et al., 2014), which prioritizes parameters with low AICc values for simulation and is considered a standard measure of the model's goodness of fit. Using the ENMevaluate function in the 'ENMeval' R package, we determined the most appropriate combination of MaxEnt features (*L*, *Q*, *P* and *H*) and regularization parameters (ranging from 1 to 4) based on the number of occurrences data for each of the six wild lentil species. The Jackknife analysis (Townsend Peterson & Cohoon, 1999) was performed to assess the relative importance of each environmental variable for the potential habitat distribution. Data for the species (*L. culinaris* subsp. *orientalis*, *L. ervoides*, *L. nigricans*, *L. lamottei*, *L. culinaris* subsp. *odemensis*) were randomly divided into 20% test data and 80% training data for model construction. The K-fold method of cross-validation was applied to partition the occurrence dataset into 10 groups for training and testing data (Burman, 1989). The

random seed selection method was employed to ensure that the model used different sets of presence records for training and testing on every replication. For *L. culinaris* subsp. *tomentosus*, which had less than 25 occurrences (12 occurrences), we used the jackknife 'Leave-one-out' method to model the distribution, this approach has been found to be ideal for modelling species with few presences records (Fielding & Bell, 1997; Pearson et al., 2007). Each observed locality was removed from the data once, and the model was built using the remaining localities. This process was repeated to create a total number of models equivalent to the presence records. The final prediction was derived by averaging all 12 models. As models based only on presence points can be highly susceptible to sample bias (Pearce & Boyce, 2006), background points were used. MaxEnt compared the locations where a species has been found to all the environments within the study area. In this way, 10,000 random points were generated within the species study area (Phillips et al., 2009).

To calibrate the model and assess its robustness, we conducted a threshold-independent receiver-operating characteristic (ROC) analysis. The ROC curve allowed us to plot the true positive rate against the false positive rate for different threshold values. In this study, we used the area under the curve (AUC), as a measure of model accuracy. The AUC values range from 0.5 to 1, with values close to 1 indicating higher prediction accuracy of the model (Bosso et al., 2016; Fois et al., 2018; Pearce & Ferrier, 2000).

2.5 | Conservation status of the *Lens* genus

2.5.1 | IUCN Red List conservation status assessments-criterion B

The IUCN Red List of Threatened Species, developed by the IUCN, is a comprehensive tool used to assess the extinction risks of plant species based on the IUCN standards and Criteria. Among these criteria, the IUCN-criterion B is the most widely applied one for official extinction risk assessments (Collen et al., 2016).

For this study, extinction assessments were conducted on a species-by-species basis. To quantify the distribution range of each species, the 'ConR' R package (Dauby et al., 2017) was used. Various metrics such as extent of occurrence (EOO), area of occupancy (AOO), number of unique coordinates, number of locations and number of locations in protected areas were calculated. These metrics were used to determine the IUCN category for each species based on its extinction risk, including Critically Endangered, Endangered, Vulnerable, Least Concerned, Near Threatened or Data Deficient in cases where insufficient data were available. AOO was calculated according to the standard recommendations from the IUCN Red List (IUCN Standards & Petitions Committee, 2017), by overlaying a 2×2 km grid over point location data. EOO was calculated by creating a minimum convex polygon around the points, with the addition of a buffer calculated based on the radius of each point.

2.5.2 | Gap analysis: Estimating the degree of representation of species in conservation repositories (ex-situ) and protected areas (in-situ)

The assessment of in and ex-situ conservation of each species was conducted using indicators developed by Khoury et al. (2019). These indicators aim to evaluate the eco-geographic variation maintained in conservation repositories that is present within protected natural areas and compare it with the full extent of eco-geographic variation predicted within the species' native ranges. The 'GapAnalysis' R package was applied to determine conservation status gaps, and priorities for conservation efforts (Carver et al., 2021; Khoury et al., 2019, 2020).

The conservation score was computed using occurrence data and a binary raster map where 0 indicates absence and 1 indicates the presence of species. Records that are currently kept in germplasm collections (genebank, seedbank or botanical garden) were scored as G, while the value H was assigned for any other reference samples (human observations, herbarium samples). Ecoregions and protected areas were retrieved from an open-access data repository (https://dataverse.harvard.edu/dataverse/GapAnalysis).

Ex-situ conservation gap analysis
This analysis estimates the degree of representation of taxa, their populations, and their underlying genetic diversity in ex-situ conservation repositories. Three scores are calculated: the Sampling Representativeness Score (SRS_{ex}) (Equation 1), The Geographical Representativeness Score (GRS_{ex}) (Equation 2), and the Ecological Representativeness Score (ERS_{ex}) (Equation 3). All scores are ranged between 0 and 100, with 0 representing an extremely poor state of conservation and 100 representing comprehensive protection.

$$SRS_{ex} = \left[\frac{\text{number of germplasm accessions } (G)}{\text{number of total reference records } (H)} \right] \times 100, \quad (1)$$

$$GRS_{ex} = \left[\frac{\text{total area } (km^2) \text{ of CA50 of all } G \text{ records}}{\text{total area } (km^2) \text{ of species distribution model (SDM)}} \right] \times 100, \quad (2)$$

$$ERS_{ex} = \left[\frac{\text{number of ecoregions represented within CA50 of } G \text{ records}}{\text{number of ecoregions represented within SDM}} \right] \times 100. \quad (3)$$

The three ex-situ scores are averaged to provide a final ex-situ conservation score (FCS_{ex}) (Equation 4). it then assigns each taxon to a priority category based on the FCS_{ex} score, with high priority (HP) for further collecting for ex-situ conservation assigned when $FCS_{ex} < 25$, medium priority (MP) where $25 \leq FCS_{ex} < 50$, low priority (LP) where $50 \leq FCS_{ex} < 75$ and sufficiently conserved (SC) for taxa whose $FCS_{ex} \geq 75$,

$$FCS_{ex} = \left[\frac{SRS + GRS_{ex} + ERS_{ex}}{3} \right]. \quad (4)$$

In-situ conservation gap analysis

This analysis assesses how the diversity of species, their populations and genetic variations are covered within protected areas as recorded in the World Database of Protected Areas (WDPA, 2019) (IUCN, 2019). This includes both land and coastal reserves that are officially recognized, designated, or established. It calculates three specific scores: the in-situ sampling representativeness score (SRS_{in}), the in-situ geographical representativeness score (GRS_{in}), and the in-situ ecological representativeness score (ERS_{in}). These scores are then averaged to determine an overall in-situ conservation score (FCS_{in}). The scoring system ranges from 0 to 100, where 0 indicates very poor conservation status and 100 signifies full conservation.

$$SRS_{in} = \left[\frac{\text{number of occurrences in protected area}}{\text{total number of occurrences}} \right] \times 100, \quad (5)$$

$$GRS_{in} = \left[\frac{\text{area } (km^2) \text{ located in protected areas}}{\text{total area } (km^2) \text{ of SDM}} \right] \times 100, \quad (6)$$

$$ERS_{in} = \left[\frac{\text{number of ecoregions represented in SDM located in protected areas}}{\text{number of ecoregions represented within SDM}} \right] \times 100 \quad (7)$$

The FCS_{in} score averages three in-situ conservation metrics (Equation 8). Following this calculation, it categorizes each species into a conservation priority level according to the FCS_{in} score. Species are designated as HP, MP, LP or SC,

$$FCS_{in} = \left[\frac{SRS_{in} + GRS_{in} + ERS_{in}}{3} \right]. \quad (8)$$

The Final Combined Conservation Score (FCS_c) (Equation 9) for each wild lentil species was then calculated by averaging both FCS_{in} and FCS_{ex}. Species with an $FCS_c < 25$ were considered a high priority for conservation whereas species with an $FCS_c > 50$ were considered as low priority. An $FCS_c > 75$ indicates species that are properly conserved,

$$FCS_c = \left[\frac{FCS_{ex} + FCS_{in}}{2} \right]. \quad (9)$$

3 | RESULTS

3.1 | Species distribution modelling

3.1.1 | Variables selection, contribution, and models performance

From an initial set of 22 environmental variables, 12 variables were selected for modelling the distribution of the six wild lentil species under both current and future climate change scenarios (Table 1). Variables exhibiting VIF exceeding 10 were excluded. The Jackknife results showed the variables that contributed the most to the distribution models of each species. For *L. culinaris* subsp. *orientalis*, *L. ervoides*, *L. nigricans* and *L. culinaris* subsp. *odemensis* the variable with the highest contribution was Bio19 (Precipitation of the Coldest Quarter),

contributing 25.1%, 51.3%, 49.4% and 51.4%, respectively. For *L. lamottei* and *L. culinaris* subsp. *tomentosus*, Bio7 (Temperature Annual Range) and Bio9 (Mean Temperature of the Driest Quarter) were the variables that contributed the most to the distribution of these species with 31.5% and 19.2%, respectively (Table 1). Furthermore, Figure S1 shows high levels of predictive performances with values of AUC training ranging between 0.953±0.009 and 0.987±0.003 for *L. culinaris* subsp. *orientalis* and *L. culinaris* subsp. *tomentosus*, respectively.

3.1.2 | Potential distribution of lentil wild species under current conditions

The modelling results were divided into five categories, where 0–0.2 was considered unsuitable, 0.2–0.4 low suitability, 0.4–0.6 moderate suitability, 0.6–0.8 high suitability and >0.8 very highly suitable. The distribution pattern of the six lentil wild species was observed to span across the Fertile Crescent region, notably intersecting in Turkey and Syria (Figure 1), revealing distinct differences in their geographic distribution. The suitable areas for *L. culinaris* subsp. *tomentosus* were mainly found in southern Turkey and northern Syria, while the distribution of *L. culinaris* subsp. *orientalis* extended extensively throughout the Fertile Crescent, encompassing Lebanon, Syria, Palestine and Cyprus, and reaching further north to Azerbaijan, Uzbekistan and Tajikistan, as shown in Figure 2a,b. In contrast, *L. culinaris* subsp. *odemensis* exhibited a restricted range, spanning from Turkey to Syria and Palestine, with scattered occurrences in northern Africa (Figure S2). In comparison, *L. ervoides* showed a wide distribution extending from Spain to Azerbaijan with high habitat suitability in Turkey, Syria and Palestine (Figure S3). On the other hand, *L. lamottei* was primarily distributed in France and Spain and extended to southern Italy and Greece (Figure S4) while *L. nigricans* was mainly distributed across the Mediterranean region (Figure S5).

3.1.3 | Potential distribution of lentil wild species under future climate scenarios

Predictions of suitable areas for both subspecies *L. culinaris* subsp. *orientalis* and *L. culinaris* subsp. *tomentosus* under the SSP2-4.5 and SSP5-8.5 scenarios in 2050 and 2070 are presented in Figure 2 (other species are presented in the Supporting Information). For *L. culinaris* subsp. *orientalis*, the prediction of the suitable area under the SSP2-4.5 scenario suggests a 3% decrease in a suitable area with a probability of occurrence greater than 0.5 in 2050. This corresponds to a reduction from 522,241.6 to 505,283.5 km² . Under the more extreme SSP5-8.5 scenario in 2070, the loss of suitable habitat is projected to be even more substantial, accounting for a 22% decrease compared to the current suitable area. For *L. culinaris* subsp. *tomentosus*, the current suitable area is estimated at 177,011.7 km² with a probability of occurrence greater than 0.5. Under the SSP2-4.5 and SSP5-8.5 scenarios, the projected decreases in suitable areas for this species are estimated to be 4% and 6% in 2050 and

TABLE 1 Environmental variables used in this study and their percentage contribution to species distribution.

| Code | Environmental variable | Unit | Source | Percent contribution (%) | | | | | |
				Lens orientalis	*L. ervoides*	*L. nigricans*	*L. odemensis*	*L. lamottei*	*L. tomentosus*
BIO2	Mean Diurnal Range (mean monthly (max – min temp))	°C	Worldclim	2.0	0.6	0.3	0.1	1.3	1.1
BIO3	Isothermality (BIO2/BIO7) (×100)	°C	-	1.4	0.8	0	0.1	0.2	0.5
BIO7	Temperature Annual Range (BIO5-BIO6)	-	-	8.0	3.2	6.2	6.0	31.5	0.1
BIO8	Mean Temperature of Wettest Quarter	-	-	4.5	1.8	0.3	0.6	0.2	12.4
BIO9	Mean Temperature of Driest Quarter	-	-	3.7	5.2	16.3	4.5	7.7	19.2
BIO12	Annual Precipitation	mm	-	19.8	15.6	1.0	0.4	6.1	-
BIO14	Precipitation of Driest Month	-	-	15.7	1.7	14.3	14.4	17.0	17.2
BIO15	Precipitation Seasonality (coeff. of var.)	-	-	6.8	9.6	0.3	17.2	9.2	-
BIO19	Precipitation of Coldest Quarter	-	-	25.1	51.3	49.4	51.4	3.8	18.7
Elevation	Elevation	m	DET	3.9	1.9	1.7	1.0	2.4	1.8
LAI	Leaf area index	-	MODIS/NASA	7.9	5.3	6.6	4.3	14.6	29.1
NDVI	Normalized difference vegetation index	-	MODIS/NASA	1.0	3.0	3.6	0	6.2	-

20% and 25% in 2070 respectively (Table 2). The analysis suggests a projected decrease in suitable areas under future climate conditions, particularly under the SSP5-8.5 scenario in 2070, with an estimated reduction of approximately 33% for *L. culinaris* subsp. *odmensis* and about 47% for *L. lamottei*. In contrast, the suitable habitat for *L. ervoides* is expected to expand by 2% under the SSP2-4.5 scenario in 2050 (Table 2). Furthermore, compared to other species, this species is expected to experience relatively less area loss under both scenarios in 2050 and 2070.

3.2 | Conservation status of lentil wild species

The combined conservation score (FCS_c) ranged from 17.85 to 37.55 across the six lentil wild species. Among these, *L. ervoides*, *L. nigricans*, and *L. culinaris* subsp. *tomentosus* were identified as a high priority for further conservation strategies with FCS_c values of 21.28,

17.85, and 21.26 respectively. While *L. culinaris* subsp. *orientalis*, *L. lamottei*, and *L. culinaris* subsp. *odemensis* was identified as a medium priority with FCS_c of 28.38 37.54, and 26.89 respectively. The FCS values indicate that none of the six lentil wild species is sufficiently conserved (FCS_c >75) (Figure 3).

The comprehensiveness of ex-situ conservation, ranging from 23.43 to 42.40, was higher than the FCS_c values. Among the six studied species, *L. nigricans* showed a high priority for ex-situ conservation with FCS_{ex} of 23.43, while the other five species were classified as medium priority (Figure 3).

For all the studied wild species, the in-situ conservation ranged from 5.68 to 32.68. Only *L. lamottei* showed a medium priority for in-situ conservation with FCS_{in} of 32.68, while the other five species *L. ervoides*, *L. nigricans*, *L. culinaris* subsp. *odemensis*, *L. culinaris* subsp. *orientalis*, and *L. culinaris* subsp. *tomentosus* showed a high priority with FCS_{in} of 5.68, 12.26, 14.01, 21.27 and 2.32 respectively (Figure 3).
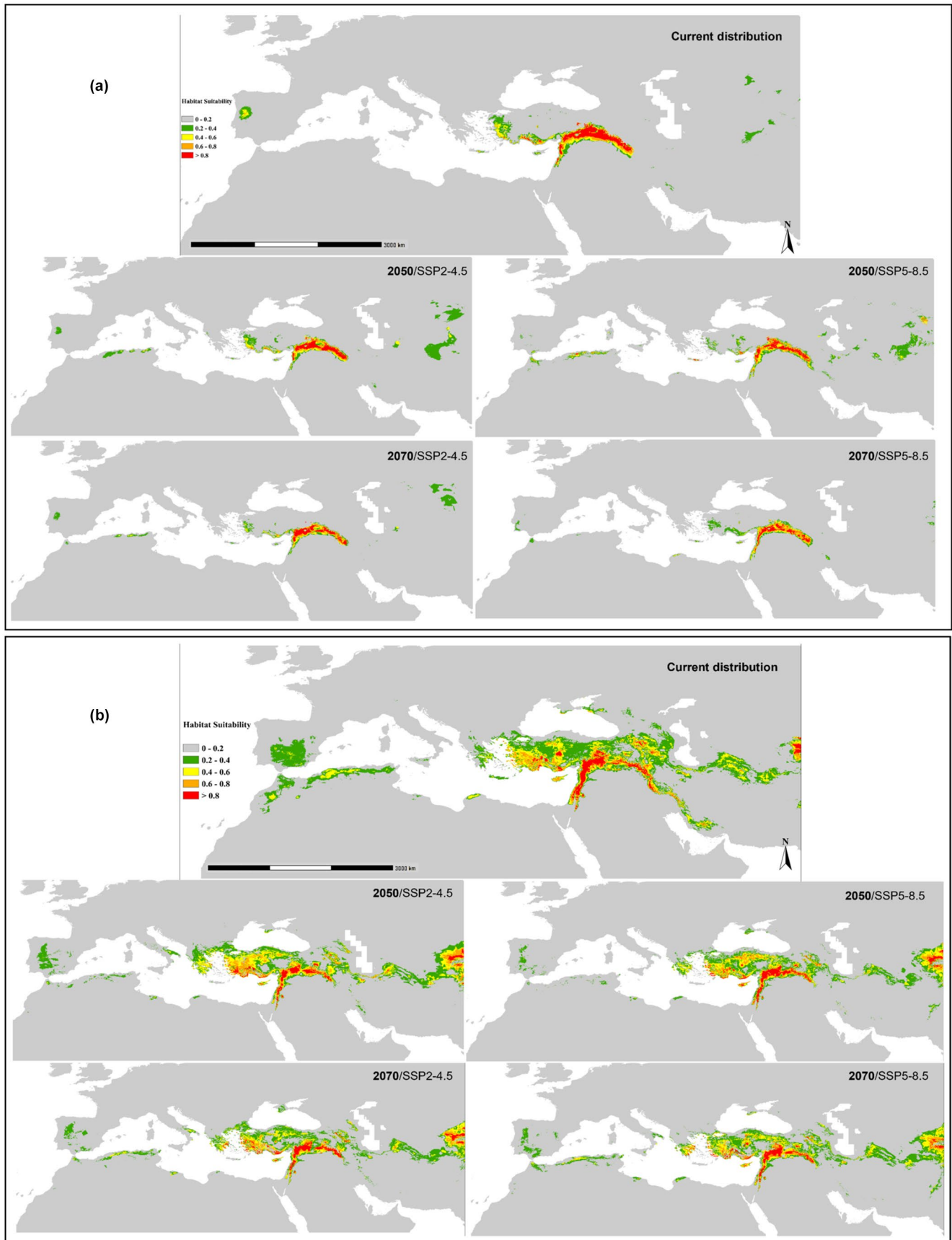
FIGURE 2 Prediction of potentially suitable habitat for *Lens culinaris* subsp. *tomentosus* (a) and *L. culinaris* subsp. *orientalis* (b) under current and future climate change scenarios SSP2-4.5 and SSP5-8.5 in 2050 and 2070. The probability of habitat suitability was classified into very high (>0.8), high (0.6–0.8), moderate (0.4–0.6), low (0.2–0.4) and unsuitable (0–0.2).

TABLE 2 Total suitable area (km^2) in the present and the predicted change in total suitable area for each wild lentil species under optimistic (SSP2-4.5) and pessimistic (SSP5-8.5) scenarios in 2050 and 2070.

| Species	Present	SSP2-4.5		SSP5-8.5	
		2050	2070	2050	2070
Lens culinaris subsp. *orientalis*	522241.6	505283.5 (−3%)	418205.4 (−20%)	438455.4 (−16%)	409154.6 (−22%)
L. culinaris subsp. *tomentosus*	177011.7	170158.2 (−4%)	141165.8 (−20%)	166644.0 (−6%)	132876.3 (−25%)
L. culinaris subsp. *odemensis*	173864.5	143158.6 (−18%)	133657.8 (−23%)	139131.3 (−20%)	117013.7 (−33%)
Lens ervoides	355324.3	356154.9 (2%)	329554.8 (−7%)	331792.3 (−7%)	318449.8 (−10%)
Lens lamottei	151194.5	109434.4 (−28%)	89218.8 (−41%)	104392.5 (−31%)	80182.2 (−47%)
Lens nigricans	428769.5	423132.3 (−1%)	387842.7 (−10%)	412819.7 (−4%)	376849.4 (−12%)
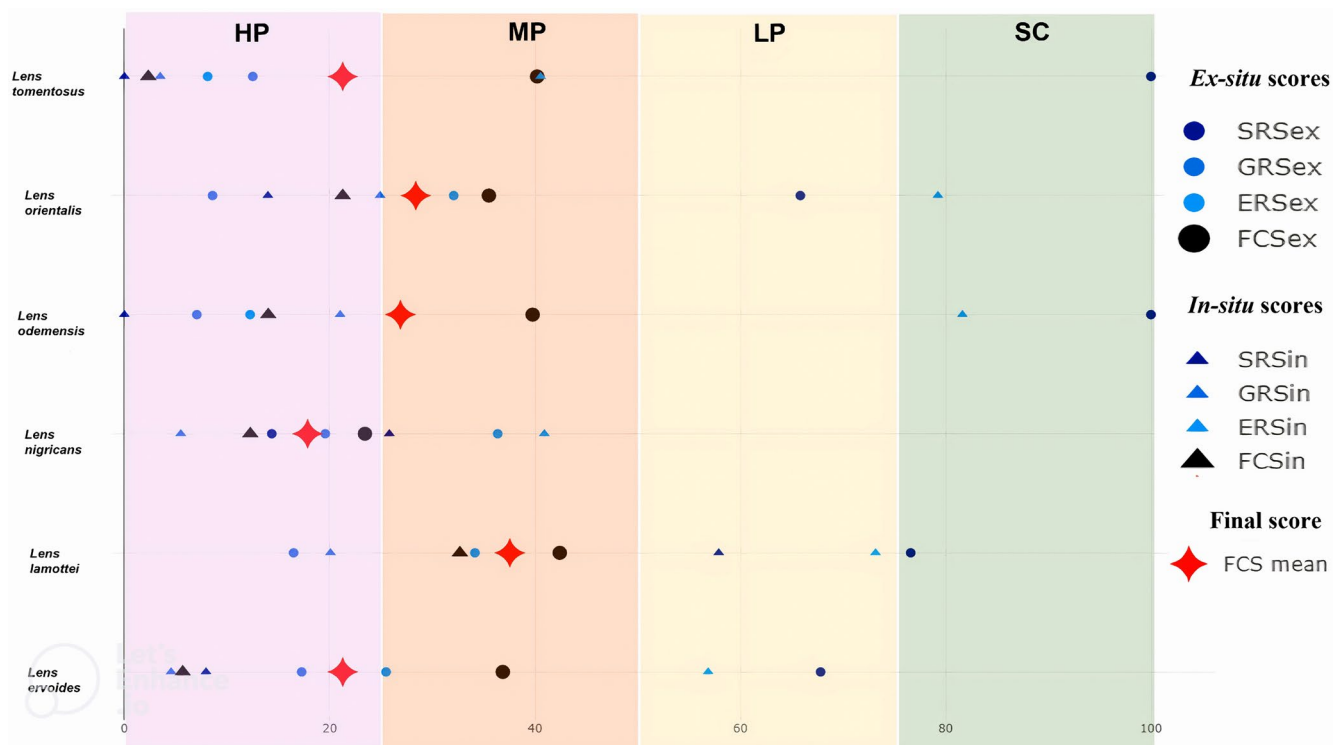
FIGURE 3 Conservation score assessment of wild lentil species. ERS$_{in}$, ecological representativeness score in-situ; ERS$_{ex}$, ecological representativeness score ex-situ; FCS$_{in}$, final conservation score in situ; FCS$_{ex}$, final conservation score ex-situ; FCS$_{mean}$, combined final conservation score; GRS$_{in}$, geographical representativeness score in-situ; GRS$_{ex}$, geographical representativeness score ex-situ; SRS$_{in}$, sampling representativeness score in-situ; SRS$_{ex}$, sampling representativeness score ex-situ.

3.3 | IUCN extinction risk assessment

According to the preliminary risk assessment using IUCN criterion B, *L. culinaris* subsp. *tomentosus* was categorized as a 'Vulnerable' species, indicating a higher risk of extinction. The other five species were considered to be of 'Least Concern' or 'Near Threatened' status, implying that they could potentially face the risk of becoming threatened in the near future. The analysis reveals that approximately 40% to 50% of wild lentil species are currently facing the threat of extinction, with Turkey and Syria identified as the most vulnerable regions. Moreover, it is within this geographical area that the wild lentil exhibits a higher level of genetic diversity (Figure S6).

4 | DISCUSSION

4.1 | Current distribution patterns of lentil wild relatives

The spatial suitability distribution of the six wild lentil species, notably centered in the Fertile Crescent and Mediterranean region. This area has been widely recognized as a biodiversity hotspot, characterized by its remarkable species richness (Figure S6a). An important aspect that emerged from our analysis is the contrasting responses to climatic variables among the six wild lentil species, despite their similar distribution patterns. Each of the six wild lentil species

exhibited distinct responses to various climatic variables, reflecting their specific ecological niche requirements and adaptations to their respective habitats. Notably, *L. culinaris* subsp. *orientalis*, *L. culinaris* subsp. *tomentosus* and *L. ervoides* showed a distinct response to temperature variations, particularly the Mean Temperature of the Driest Quarter (BIO9) resulting in broad Gaussian distributions (Figure S7). On the other hand, *L. nigricans*, *L. culinaris* subsp. *odemensis* and *L. lamottei* showed a more restricted response to BIO9, exhibiting distributions centered around a temperature of 20–25°C. The observed tolerance to temperature exhibited by *L. culinaris* subsp. *orientalis* and *L. ervoides* can be linked to the range of their distribution across regions known for their limited and low rainfall, such as Syria, Jordan, Tajikistan and Azerbaijan. These arid and dry regions are characterized by limited water availability and periodic drought conditions, making them challenging environments for many plant species (Coyne et al., 2020; Gupta & Sharma, 2006). The likelihood of *L. culianris* subsp. *tomentosus* occurrence exhibited a gradual increase, attaining a value of around 0.8 as the Temperature of the Driest Quarter (BIO9) approached 35°C. Subsequently, as the temperature neared 37°C, the probability of occurrence reached a plateau, maintaining constant at 0.85 (Figure S7). Previous studies have reported that *L. culinaris* subsp. *tomentosus* is a valuable source for drought and high temperature tolerance traits, achieved through physiological mechanisms such as low transpiration rate (Gorim & Vandenberg, 2017; Rouichi et al., 2023). An important aspect of our study, especially regarding *L. culinaris* subsp. *tomentosus*, is the model's effectiveness in handling limited occurrence records. Our findings align with various research efforts that have tested the MaxEnt modelling algorithm, emphasizing its sensitivity to the number of occurrence records and its robustness even when data are scarce. Studies by Støa et al. (2019) and Pearson et al. (2007) have shown that MaxEnt can significantly exceed random prediction accuracy with as few as 5–10 presence records, suggesting a guideline of employing MaxEnt modelling with a minimum of 10–15 presence records for meaningful outcomes. Despite the limited number of occurrences, MaxEnt's performance is highly successful and statistically significant, illustrating its suitability for modelling distributions with limited data. This capability is further highlighted when compared to other methods, with MaxEnt outperforming alternatives like Bioclim, Domain and GARP models across various species and sample sizes (Hernandez et al., 2006). Nonetheless, the determination of a minimum threshold for occurrence records becomes particularly crucial for modelling invasive plant species that have broad distributions. Morán-Ordóñez et al. (2017) demonstrated that the variability in model predictive performance over time was closely linked to the geographic range of the species or the study area. Specifically, models for species with wide geographical ranges were generally less accurate than those for species confined to more localized areas, this is particularly relevant for *L. culinaris* subsp. *tomentosus*, which has a narrow distribution confined to specific regions of Turkey and Syria (Boyraz Topaloğlu et al., 2023; Coyne et al., 2020). For some species, a limited set of sampling localities might be sufficient to model their environmental niche accurately. Conversely, for species exhibiting broad geographical distributions, an identical sample size may prove insufficient to encompass the range of conditions within which the species is found.

The restricted distribution of *L. lamottei* in Europe can be attributed to its specific temperature requirements ranging from 15 to 22°C for optimal growth and survival. Our study highlights how MaxEnt effectively addresses the challenges and constraints encountered in alternative modelling approaches, especially with limited occurrences data. It highlights the necessity of adjusting model features and regularization settings for each species, based on available occurrence data, a process simplified by the 'ENMeval' package in R. However, interpreting SDM models requires caution; they should not be considered as actual limits to the range of species. Rather, we interpret the modelled distributions as areas likely to have similar environmental conditions where these species are found. These findings can be used to explore and identify potential new locations where undiscovered populations may exist which can offer a significant advantage for biological research, risk assessment and In-situ conservation. Research on the collection, use, management, and conservation of plant genetic resources, along with their habitats and environmental impacts, is essential to continuously inform and adjust conservation strategies. Collaboration at national, regional, and international levels is crucial to addressing these needs and mitigating threats to plant conservation, including those posed by climate change and related challenges.

4.2 | Future distribution patterns of lentil wild relatives

Significant changes in lentil CWR distribution are anticipated in response to climate change. These changes will depend on the prevailing climatic conditions. Recent simulation studies have highlighted the significant negative impact of climate change as a primary driver of future habitat degradation, fragmentation and ultimately, biodiversity loss (Abdelaal et al., 2019; Davis et al., 2012; Gebrewahid et al., 2020; Jarvis et al., 2008; Mishra et al., 2021; Yi et al., 2016; Zhang et al., 2018). Understanding how lentil wild species may respond to changing environmental conditions could help in defining effective and specific conservation and management strategies for these species (Ferrer et al., 2002).

Using different models, a general decrease of the suitable area was observed for all lentil wild species with a probability of occurrence higher than 0.5. While most of the species exhibited a decrease in suitable areas, *L. ervoides* showed a slight increase (2%), especially under the SSP2-4.5/2050 scenario. This particular response observed for *L. ervoides* brings evidence of its potential adaptation to future climatic conditions. Both *L. ervoides* and *L. nigricans* stand out as the species that will be subjected to the least distribution area loss under climate change, with estimated respective decreases of 10% and 12% under the severe scenario (SSP5-8.5) in 2070. These two species have been reported to be drought tolerant compared to the other wild lentil species (Coyne et al., 2020; Gupta & Sharma, 2006; Hamdi & Erskine, 1996).

The species, *L. lamottei*, *L. culianris* subsp. *tomentosus*, and *L. culinaris* subsp. *odemensis,* have currently relatively restricted suitable areas, covering each less than 200,000 km². Under the SSP5-8.5 climate change scenario in 2070, MaxEnt predictions revealed significant future losses in the habitat suitable area with estimated decreases of 47%, 33% and 25% for *L. lamottei*, *L. culinaris* subsp. *odemensis* and *L. culinaris* subsp. *tomentosus*, respectively. This is in line with previous studies which reported that species with limited geographical ranges typically exhibit restricted ecological adaptability and tend to be more vulnerable to the impact of climate change when compared to those with widespread distributions (Ma & Sun, 2018; Zhang et al., 2022).

4.3 | Wild lentil species: Risk assessment and conservation status

CWRs play an essential role in the current and upcoming food security strategies, they are a potential source of diversity for domesticated species. Lentil wild relatives have shown good resistance to diverse biotic and abiotic stress (Coyne et al., 2020; Gorim & Vandenberg, 2017; Gupta & Sharma, 2006; Hamdi & Erskine, 1996; Rouichi et al., 2023; Singh et al., 2014).

The region characterized by the highest species richness for wild lentil species is situated within the Fertile Crescent, with an overlap encompassing both Turkey and Syria, as shown in Figure S6a. The Fertile Crescent is a geographical area reported in various studies for its rich plant species diversity. A total of 835 species were identified as CWRs with significant socio-economic value to the region. This area is recognized as a domestication centre for major crops including lentils (Vincent et al., 2013; Zair et al., 2018). It is a remarkable prevalence of the five wild lentil species richness. Our preliminary IUCN risk assessment highlighted *L. culinaris* subsp. *tomentosus* as the most vulnerable species among the *Lens* genus, emphasizing the urgent need for conservation priority action and efforts for this species. The remaining species, *L. culinaris* subsp. *orientalis*, *L. ervoides*, *L. lamottei*, *L. nigricans* and *L. culinaris* subsp. *odemensis* showed either least concern or near

threatened species status (Table 3). In addition to increasing political unrests and conflicts, The ecological integrity of the Fertile Crescent region faces substantial threats associated with climate change, habitat destruction, and resource over-exploitation, resulting in a considerable decline in biodiversity (Malhotra et al., 2019). Our study showed that the loss of diversity in wild lentil species ranged from 20% to 50% (Figure S6b). In the assessment of species' conservation statuses within protected areas, it is conventionally presupposed that such species are sufficiently safeguarded. However, this presupposition frequently proves to be inaccurate. It is imperative to recognize that the mere presence of plant species within these protected zones does not inherently ensure their protection. Such nuanced perspective underlines the complexity of conservation (Mertens et al., 2021). Moreover, the region is presently grappling with a wide range of additional challenges, encompassing not only conflicts and political unrest but also vulnerability to natural disasters, particularly seismic activity. These diverse challenges compound the risks to the conservation of genetic diversity within wild lentil species.

The Gap Analysis assessment designated the three species, *L. lamottei*, *L. culinaris* subsp. *odemensis* and *L. culinaris* subsp. *orientalis* with medium priority for both in-situ and ex-situ conservation, while *L. culinaris* subsp. *tomentosus*, *L. nigricans* and *L. ervoides* were designated with high priority. Despite the conservation efforts, our study revealed that none of the six wild lentil species are currently sufficiently conserved both in-situ and ex-situ, emphasizing the necessity for immediate and targeted conservation actions to protect their genetic diversity and ensure their long-term survival. Our findings provide a scientific basis for targeted conservation and management strategies, including: (i) protecting and restoring degraded habitats through the establishment of protected areas and ecosystem rehabilitation efforts; (ii) prioritizing in-situ and ex-situ conservation for highly endangered species, such as *L. lamottei*, *L. culinaris* subsp. *tomentosus* and *L. culinaris* subsp. *odemensis,* by enhancing monitoring of wild lentil populations and securing financial support for these strategies; (iii) strengthening legal protections to safeguard these endangered wild species, regulate the sustainable use of genetic resources and mitigate activities that threaten plant biodiversity; and

TABLE 3 Partial assessment of risk of extinction of the six wild lentil species based on IUCN criterion B.

Species	EOO	EOO category	AOO	AOO category	Criterion B category
Lens culinaris subsp. *orientalis*	61,186,140	LC or NT	1732	LC or NT	LC or NT
L. culinaris subsp. *tomentosus*	170,722	LC or NT	44	VU	VU
L. culinaris subsp. *odemensis*	2,097,682	LC or NT	256	LC or NT	LC or NT
Lens ervoides	10,593,475	LC or NT	1476	LC or NT	LC or NT
Lens lamottei	22,787,577	LC or NT	576	LC or NT	LC or NT
Lens nigricans	3,359,680	LC or NT	264	LC or NT	LC or NT

Note: AOO, area of occupancy (in km²); EOO, extent of occurrence (in km²). IUCN categories are determined and designated as follows: LC (Least Concern), NT (Near Threatened), VU (Vulnerable) and EN (Endangered).

(iv) promoting agroforestry and sustainable land management practices to reduce habitat destruction and degradation.

Yet, the increasing and more pronounced impacts of climate change needs urgent action for setting up a more active networks for an effective in-situ biodiversity conservation. Doubts are emerging about the long-term effectiveness of protected areas in preserving biodiversity. Despite the global significance of CWR and international emphasis on their in-situ conservation through treaties, conventions, and academic research, evidence of practical conservation efforts remains minimal. The Fertile Crescent, home to a significant diversity of wild lentil species, lacks adequate protected areas, highlighting a gap in conservation efforts (Shehadeh et al., 2013). Our findings should help guide the future actions and recommendations for lentil CWR conservation and management strategies in the Fertile Crescent and other potential regions. This requires the involvement and engagement of various stakeholders, including national research systems, local communities, NGOs, the private sector, and international institutions, in conservation efforts through Protected Areas and Plant Conservation Networks. The CGIAR—International Center for Agriculture Research in the Dray Areas (ICARDA) which has the global mandate for Lentil, with other potential national and international institutions and genebanks initiatives such as the Crop Trust could play key role for future actions. These networks will strengthen the protection, restoration, and rehabilitation of endangered species in their natural habitats. Furthermore, campaigns and educational programs should be organized to raise awareness about the importance of plant conservation.

5 | CONCLUSION

In conclusion, our research highlights the importance of considering species-specific ecological traits and vulnerabilities when formulating conservation strategies. Given the pressing issues presented by climate change, habitat degradation, political unrest, and natural disasters addressing the conservation needs of these wild lentil species is of utmost importance. The findings of this study provide a foundation for informed decision-making, facilitating the protection of invaluable genetic resources and the maintenance of biodiversity in this critical region.

ORCID
Michel Edmond Ghanem https://orcid.org/0000-0003-0626-7622
Moez Amri https://orcid.org/0000-0002-4707-0618

REFERENCES
Abdelaal, M., Fois, M., Fenu, G., & Bacchetta, G. (2019). Using MaxEnt modeling to predict the potential distribution of the endemic plant *Rosa arabica* Crép in Egypt. *Ecological Informatics*, *50*, 68–75. https://doi.org/10.1016/j.ecoinf.2019.01.003

Aiello-Lammens, M. E., Boria, R. A., Radosavljevic, A., Vilela, B., & Anderson, R. P. (2015). spThin: An R package for spatial thinning of species occurrence records for use in ecological niche models. *Ecography*, *38*(5), 541–545. https://doi.org/10.1111/ecog.01132

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Bosso, L., Di Febbraro, M., Cristinzio, G., Zoina, A., & Russo, D. (2016). Shedding light on the effects of climate change on the potential distribution of *Xylella fastidiosa* in the Mediterranean basin. *Biological Invasions*, *18*(6), 1759–1768. https://doi.org/10.1007/s10530-016-1118-1

Boyraz Topaloğlu, Ş., Karacaoğlu, Ç., & Çağlar, S. S. (2023). Potential impacts of climate change on wild relatives of lentil (*Lens* spp.): An ecological niche model approach. *Flora*, *307*, 152372. https://doi.org/10.1016/j.flora.2023.152372

Brum, F. T., Graham, C. H., Costa, G. C., Hedges, S. B., Penone, C., Radeloff, V. C., Rondinini, C., Loyola, R., & Davidson, A. D. (2017). Global priorities for conservation across multiple dimensions of mammalian diversity. *Proceedings of the National Academy of Sciences of the National Academy of Sciences of the United States of America*, *114*(29), 7641–7646. https://doi.org/10.1073/pnas.1706461114

Burman, P. (1989). A comparative study of ordinary cross-validation, *v*-fold cross-validation and the repeated learning-testing methods. *Biometrika*, *76*(3), 503–514. https://doi.org/10.1093/biomet/76.3.503

Carver, D., Sosa, C. C., Khoury, C. K., Achicanoy, H. A., Diaz, M. V., Sotelo, S., Castañeda-Álvarez, N. P., & Ramirez-Villegas, J. (2021). GapAnalysis: An R package to calculate conservation indicators using spatial information. *Ecography*, *44*(7), 1000–1009. https://doi.org/10.1111/ecog.05430

Castañeda-Álvarez, N. P., Khoury, C. K., Achicanoy, H. A., Bernau, V., Dempewolf, H., Eastwood, R. J., Guarino, L., Harker, R. H., Jarvis,

A., Maxted, N., Müller, J. V., Ramirez-Villegas, J., Sosa, C. C., Struik, P. C., Vincent, H., & Toll, J. (2016). Global conservation priorities for crop wild relatives. *Nature Plants*, *2*(4), 16022. https://doi.org/10.1038/nplants.2016.22

Cavender-Bares, J., Gamon, J. A., Townsend, P. A., & (Éds.). (2020). *Remote sensing of plant biodiversity*. Springer International Publishing. https://doi.org/10.1007/978-3-030-33157-3

Collen, B., Dulvy, N. K., Gaston, K. J., Gärdenfors, U., Keith, D. A., Punt, A. E., Regan, H. M., Böhm, M., Hedges, S., Seddon, M., Butchart, S. H. M., Hilton-Taylor, C., Hoffmann, M., Bachman, S. P., & Akçakaya, H. R. (2016). Clarifying misconceptions of extinction risk assessment with the IUCN Red List. *Biology Letters*, *12*(4), 20150843. https://doi.org/10.1098/rsbl.2015.0843

Costa-Pinto, A. L. D., Bovendorp, R. S., Heming, N. M., Malhado, A. C., & Ladle, R. J. (2024). Where could they go? Potential distribution of small mammals in the Caatinga under climate change scenarios. *Journal of Arid Environments*, *221*, 105133. https://doi.org/10.1016/j.jaridenv.2024.105133

Coyne, C. J., Kumar, S., Wettberg, E. J. B., Marques, E., Berger, J. D., Redden, R. J., Ellis, T. H. N., Brus, J., Zablatzká, L., & Smýkal, P. (2020). Potential and limits of exploitation of crop wild relatives for pea, lentil, and chickpea improvement. *Legume Science*, *2*(2), 36. https://doi.org/10.1002/leg3.36

Dauby, G., Stévart, T., Droissart, V., Cosiaux, A., Deblauwe, V., Simo-Droissart, M., Sosef, M. S. M., Lowry, P. P., Schatz, G. E., Gereau, R. E., & Couvreur, T. L. P. (2017). *ConR*: An R package to assist large-scale multispecies preliminary conservation assessments using distribution data. *Ecology and Evolution*, *7*(24), 11292–11303. https://doi.org/10.1002/ece3.3704

Davis, A. P., Gole, T. W., Baena, S., & Moat, J. (2012). The impact of climate change on indigenous arabica coffee (*Coffea arabica*): Predicting future trends and identifying priorities. *PLoS One*, *7*(11), e47981. https://doi.org/10.1371/journal.pone.0047981

Elith, J., Kearney, M., & Phillips, S. (2010). The art of modelling range-shifting species. *Methods in Ecology and Evolution*, *1*(4), 330–342. https://doi.org/10.1111/j.2041-210X.2010.00036.x

Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists: Statistical explanation of MaxEnt. *Diversity and Distributions*, *17*(1), 43–57. https://doi.org/10.1111/j.1472-4642.2010.00725.x

Ferguson, M. E., Ford-Lloyd, B. V., Robertson, L. D., Maxted, N., & Newbury, H. J. (1998). Mapping the geographical distribution of genetic variation in the genus *Lens* for the enhanced conservation of plant genetic diversity. *Molecular Ecology*, *7*(12), 1743–1755. https://doi.org/10.1046/j.1365-294x.1998.00513.x

Ferguson, M. E., Maxted, N., Slageren, M. V., & Robertson, L. D. (2000). A re-assessment of the taxonomy of *Lens* Mill. (Leguminosae, Papilionoideae, Vicieae). *Botanical Journal of the Linnean Society*, *133*(1), 41–59. https://doi.org/10.1111/j.1095-8339.2000.tb01536.x

Ferrier, S., Drielsma, M., Manion, G., & Watson, G. (2002). Extended statistical approaches to modelling spatial pattern in biodiversity in northeast New South Wales. II. Community-level modelling. *Biodiversity and Conservation*, *11*, 2309–2338.

Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*(12), 4302–4315. https://doi.org/10.1002/joc.5086

Fielding, A. H., & Bell, J. F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation*, *24*(1), 38–49. https://doi.org/10.1017/S0376892997000088

Fois, M., Cuena-Lombraña, A., Fenu, G., & Bacchetta, G. (2018). Using species distribution models at local scale to guide the search of poorly known species: Review, methodological issues and future directions. *Ecological Modelling*, *385*, 124–132. https://doi.org/10.1016/j.ecolmodel.2018.07.018

GBIF.org User. (2022a). *Occurrence download* (p. 3654) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.GMSVD2

GBIF.org User. (2022b). *Occurrence download* (p. 3980) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.PEKZHD

GBIF.org User. (2022c). *Occurrence download* (p. 0) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.F5BWWS

GBIF.org User. (2022d). *Occurrence download* (p. 63227) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.FTZYGX

GBIF.org User. (2022e). *Occurrence download* (p. 75278) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.QPQH32

GBIF.Org User. (2022f). *Occurrence download* (p. 147332) [Darwin Core Archive]. [object Object]. https://doi.org/10.15468/DL.SENDS5

Gebrewahid, Y., Abrehe, S., Meresa, E., Eyasu, G., Abay, K., Gebreab, G., Kidanemariam, K., Adissu, G., Abreha, G., & Darcha, G. (2020). Current and future predicting potential areas of *Oxytenanthera abyssinica* (A. Richard) using MaxEnt model under climate change in Northern Ethiopia. *Ecological Processes*, *9*(1), 6. https://doi.org/10.1186/s13717-019-0210-8

Gorim, L. Y., & Vandenberg, A. (2017). Evaluation of wild lentil species as genetic resources to improve drought tolerance in cultivated lentil. *Frontiers in Plant Science*, *8*, 1129. https://doi.org/10.3389/fpls.2017.01129

Gorim, L. Y., & Vandenberg, A. (2018). Can wild lentil genotypes help improve water use and transpiration efficiency in cultivated lentil? *Plant Genetic Resources: Characterization and Utilization*, *16*(5), 459–468. https://doi.org/10.1017/S1479262117000399

Guarino, L., Jarvis, A., Hijmans, R. J., & Maxted, N. (2002). Geographic information systems (GIS) and the conservation and use of plant genetic resources. In J. M. M. Engels, V. Ramanatha Rao, A. H. D. Brown, & M. T. Jackson (Eds.), *Managing plant genetic diversity. Proceedings of an International Conference* (1st ed., pp. 387–404). Kuala Lumpur, Malaysia, 12–16 June 2000. CABI Publishing. https://doi.org/10.1079/9780851995229.0387

Guarino, L., & Lobell, D. B. (2011). A walk on the wild side. *Nature Climate Change*, *1*(8), 374–375. https://doi.org/10.1038/nclimate1272

Guillera-Arroita, G., Lahoz-Monfort, J. J., Elith, J., Gordon, A., Kujala, H., Lentini, P. E., McCarthy, M. A., Tingley, R., & Wintle, B. A. (2015). Is my species distribution model fit for purpose? Matching data and models to applications. *Global Ecology and Biogeography*, *24*(3), 276–292. https://doi.org/10.1111/geb.12268

Gupta, D., & Sharma, S. K. (2006). Evaluation of wild *Lens* taxa for agromorphological traits, fungal diseases and moisture stress in north western Indian Hills. *Genetic Resources and Crop Evolution*, *53*(6), 1233–1241. https://doi.org/10.1007/s10722-005-2932-y

Hamdi, A., & Erskine, W. (1996). Reaction of wild species of the geneus *Lens* to drought. *Euphytica*, *91*(2), 173–179. https://doi.org/10.1007/BF00021067

Hernandez, P. A., Graham, C. H., Master, L. L., & Albert, D. L. (2006). The effect of sample size and species characteristics on performance of different species distribution modeling methods. *Ecography*, *29*(5), 773–785. https://doi.org/10.1111/j.0906-7590.2006.04700.x

Heywood, V., Casas, A., Ford-Lloyd, B., Kell, S., & Maxted, N. (2007). Conservation and sustainable use of crop wild relatives. *Agriculture, Ecosystems & Environment*, *121*(3), 245–255. https://doi.org/10.1016/j.agee.2006.12.014

IUCN Standards and Petitions Committee. (2017). Guidelines for using the IUCN Red List - categories and criteria. Version 14. (Vol. 11, Issue February). Prepared by the Standards and Petitions Committee. http://www.iucnredlist.org/documents/RedListGuidelines.pdf

Jarvis, A., Lane, A., & Hijmans, R. J. (2008). The effect of climate change on crop wild relatives. *Agriculture, Ecosystems & Environment*, *126*(1–2), 13–23. https://doi.org/10.1016/j.agee.2008.01.013

Khazaei, H., Caron, C. T., Fedoruk, M., Diapari, M., Vandenberg, A., Coyne, C. J., McGee, R., & Bett, K. E. (2016). Genetic diversity of cultivated lentil (*Lens culinaris* Medik.) and its relation to the world's

agro-ecological zones. *Frontiers in Plant Science, 7*, 1093. https://doi.org/10.3389/fpls.2016.01093

Khoury, C. K., Amariles, D., Soto, J. S., Diaz, M. V., Sotelo, S., Sosa, C. C., Ramírez-Villegas, J., Achicanoy, H. A., Velásquez-Tibatá, J., Guarino, L., León, B., Navarro-Racines, C., Castañeda-Álvarez, N. P., Dempewolf, H., Wiersema, J. H., & Jarvis, A. (2019). Comprehensiveness of conservation of useful wild plants: An operational indicator for biodiversity and sustainable development targets. *Ecological Indicators, 98*, 420–429. https://doi.org/10.1016/j.ecolind.2018.11.016

Khoury, C. K., Carver, D., Kates, H. R., Achicanoy, H. A., Zonneveld, M., Thomas, E., Heinitz, C., Jarret, R., Labate, J. A., Reitsma, K., Nabhan, G. P., & Greene, S. L. (2020). Distributions, conservation status, and abiotic stress tolerance potential of wild cucurbits (*Cucurbita* L.). *Plants, People, Planet, 2*(3), 269–283. https://doi.org/10.1002/ppp3.10085

Ma, B., & Sun, J. (2018). Predicting the distribution of *Stipa purpurea* across the Tibetan Plateau via the MaxEnt model. *BMC Ecology, 18*(1), 10. https://doi.org/10.1186/s12898-018-0165-0

Malhotra, N., Panatu, S., Singh, B., Negi, N., Singh, D., Singh, M., & Chandora, R. (2019). Genetic resources: Collection, conservation, characterization and maintenance. In M. Singh (Ed.), *Lentils* (pp. 21–41). Elsevier. https://doi.org/10.1016/B978-0-12-813522-8.00003-0

Mammadov, J., Buyyarapu, R., Guttikonda, S. K., Parliament, K., Abdurakhmonov, I. Y., & Kumpatla, S. P. (2018). Wild relatives of maize, rice, cotton, and soybean: Treasure troves for tolerance to biotic and abiotic stresses. *Frontiers in Plant Science, 9*, 886. https://doi.org/10.3389/fpls.2018.00886

Maxted, N., & Kell, S. (2009). *Establishment of a global network for the in situ conservation of crop wild relatives: Status and needs*. FAO.

Maxted, N., Castaneda-Alvarez, N., Vincent, H., & Magos Brehm, J. (2011). Gap analysis: A tool forgenetic conservation. In L. Guarino, V. R. Rao, & E. Goldberg (Eds.), *Collecting plant genetic diversity: Technical guidelines*. Bioversity International. https://cropgenebank.sgrp.cgiar.org/index.php/procedures-mainmenu-243/collecting

Merow, C., Smith, M. J., & Silander, J. A. (2013). A practical guide to MaxEnt for modeling species' distributions: What it does, and why inputs and settings matter. *Ecography, 36*(10), 1058–1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x

Mertens, A., Swennen, R., Rønsted, N., Vandelook, F., Panis, B., Sachter-Smith, G., Vu, D. T., & Janssens, S. B. (2021). Conservation status assessment of banana crop wild relatives using species distribution modelling. *Diversity and Distributions, 27*(4), 729–746. https://doi.org/10.1111/ddi.13233

Mishra, A. (2023). International treaty on plant genetic resources for food and agriculture. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4474036

Mishra, S. N., Kumar, D., Kumar, B., & Tiwari, S. (2021). Assessing impact of varying climatic conditions on distribution of *Buchanania cochinchinensis* in Jharkhand using species distribution modeling approach. *Current Research in Environmental Sustainability, 3*, 100025. https://doi.org/10.1016/j.crsust.2021.100025

Morán-Ordóñez, A., Lahoz-Monfort, J. J., Elith, J., & Wintle, B. A. (2017). Evaluating 318 continental-scale species distribution models over a 60-year prediction horizon: What factors influence the reliability of predictions? *Global Ecology and Biogeography, 26*(3), 371–384. https://doi.org/10.1111/geb.12545

Muscarella, R., Galante, P. J., Soley-Guardia, M., Boria, R. A., Kass, J. M., Uriarte, M., & Anderson, R. P. (2014). ENMeval: An R package for conducting spatially independent evaluations and estimating optimal model complexity for Maxent ecological niche models. *Methods in Ecology and Evolution, 5*(11), 1198–1205. https://doi.org/10.1111/2041-210X.12261

Naimi, B., Hamm, N. A. S., Groen, T. A., Skidmore, A. K., & Toxopeus, A. G. (2014). Where is positional uncertainty a problem for species distribution modelling? *Ecography, 37*(2), 191–203. https://doi.org/10.1111/j.1600-0587.2013.00205.x

Pearce, J., & Ferrier, S. (2000). An evaluation of alternative algorithms for fitting species distribution models using logistic regression. *Ecological Modelling, 128*(2–3), 127–147. https://doi.org/10.1016/S0304-3800(99)00227-6

Pearce, J. L., & Boyce, M. S. (2006). Modelling distribution and abundance with presence-only data. *Journal of Applied Ecology, 43*(3), 405–412. https://doi.org/10.1111/j.1365-2664.2005.01112.x

Pearson, R. G., Raxworthy, C. J., Nakamura, M., & Townsend Peterson, A. (2007). Species distributions from small numbers of occurrence records: A test case using cryptic geckos in Madagascar. *Journal of Biogeography, 34*(1), 102–117. https://doi.org/10.1111/j.1365-2699.2006.01594.x

Phillips, J., Magos Brehm, J., van Oort, B., Asdal, Å., Rasmussen, M., & Maxted, N. (2017). Climate change and national crop wild relative conservation planning. *Ambio, 46*(6), 630–643. https://doi.org/10.1007/s13280-017-0905-y

Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: An open-source release of Maxent. *Ecography, 40*(7), 887–893. https://doi.org/10.1111/ecog.03049

Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling, 190*(3–4), 231–259. https://doi.org/10.1016/j.ecolmodel.2005.03.026

Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., & Ferrier, S. (2009). Sample selection bias and presence-only distribution models: Implications for background and pseudo-absence data. *Ecological Applications, 19*(1), 181–197. https://doi.org/10.1890/07-2153.1

Phillips, S. J., Dudík, M., & Schapire, R. E. (2004). A maximum entropy approach to species distribution modeling. *Twenty-First International Conference on Machine Learning - ICML '04*, p. 83. https://doi.org/10.1145/1015330.1015412

Porfirio, L. L., Harris, R. M. B., Lefroy, E. C., Hugh, S., Gould, S. F., Lee, G., Bindoff, N. L., & Mackey, B. (2014). Improving the use of species distribution models in conservation planning and management under climate change. *PLoS ONE, 9*(11), e113749. https://doi.org/10.1371/journal.pone.0113749

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O'Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rouichi, S., Ghanem, M. E., & Amri, M. (2024a). In-situ and ex-situ conservation priorities and distribution of lentil wild relatives under climate change: A modeling approach. *Zenodo*. https://doi.org/10.5281/ZENODO.13982974

Rouichi, S., Ghanem, M. E., & Amri, M. (2024b). In-situ and ex-situ conservation priorities and distribution of lentil wild relatives under climate change: A modeling approach. *Dryad*. https://doi.org/10.5061/DRYAD.PVMCVDNVS

Rouichi, S., Idrissi, O., Sohail, Q., Marrou, H., Hejjaoui, K., Amri, M., & Ghanem, M. E. (2023). Limited-transpiration trait in response to high VPD from wild to cultivated species: Study of the *Lens* genus. *Journal of Experimental Botany, 74*, 4875–4887.

Shehadeh, A., Amri, A., & Maxted, N. (2013). Ecogeographic survey and gap analysis of *Lathyrus* L. species. *Genetic Resources and Crop Evolution, 60*(7), 2101–2113. https://doi.org/10.1007/s10722-013-9977-0

Singh, M., Bisht, I. S., Kumar, S., Dutta, M., Bansal, K. C., Karale, M., Sarker, A., Amri, A., Kumar, S., & Datta, S. K. (2014). Global wild annual Lens collection: A potential resource for lentil genetic base broadening and yield enhancement. *PLoS One, 9*(9), e107781. https://doi.org/10.1371/journal.pone.0107781

Smýkal, P., Coyne, C. J., Ambrose, M. J., Maxted, N., Schaefer, H., Blair, M. W., Berger, J., Greene, S. L., Nelson, M. N., Besharat, N., Vymyslický, T., Toker, C., Saxena, R. K., Roorkiwal, M., Pandey, M. K., Hu, J., Li, Y. H., Wang, L. X., Guo, Y., … Varshney, R. K. (2015). Legume crops phylogeny and genetic diversity for science and breeding. *Critical Reviews in Plant Sciences*, *34*(1–3), 43–104. https://doi.org/10.1080/07352689.2014.897904

Støa, B., Halvorsen, R., Stokland, J. N., & Gusarov, V. I. (2019). How much is enough? Influence of number of presence observations on the performance of species distribution models. *Sommerfeltia*, *39*(1), 1–28. https://doi.org/10.2478/som-2019-0001

Townsend Peterson, A., & Cohoon, K. P. (1999). Sensitivity of distributional prediction algorithms to geographic data completeness. *Ecological Modelling*, *117*(1), 159–164. https://doi.org/10.1016/S0304-3800(99)00023-X

Vincent, H., Wiersema, J., Kell, S., Fielder, H., Dobbie, S., Castañeda-Álvarez, N. P., Guarino, L., Eastwood, R., León, B., & Maxted, N. (2013). A prioritized crop wild relative inventory to help underpin global food security. *Biological Conservation*, *167*, 265–275. https://doi.org/10.1016/j.biocon.2013.08.011

WCSP. (2022). *World checklist of selected plant families*. Facilitated by the Royal Botanic Gardens. http://wcsp.science.kew.org

World Database on Protected Areas (WDPA). (2019). Interface to the world database on protected areas. https://www.iucn.org/theme/protected-areas/our-work/quality-and-effectiveness/world-database-protected-areas-wdpa

Yi, Y., Cheng, X., Yang, Z.-F., & Zhang, S.-H. (2016). Maxent modeling for predicting the potential distribution of endangered medicinal plant (*H. riparia* Lour) in Yunnan, China. *Ecological Engineering*, *92*, 260–269. https://doi.org/10.1016/j.ecoleng.2016.04.010

Yoon, S., & Lee, W.-H. (2021). Methodological analysis of bioclimatic variable selection in species distribution modeling with application to agricultural pests (*Metcalfa pruinosa* and *Spodoptera litura*). *Computers and Electronics in Agriculture*, *190*, 106430. https://doi.org/10.1016/j.compag.2021.106430

Zair, W., Maxted, N., & Amri, A. (2018). Setting conservation priorities for crop wild relatives in the fertile crescent. *Genetic Resources and Crop Evolution*, *65*(3), 855–863. https://doi.org/10.1007/s10722-017-0576-3

Zair, W., Maxted, N., Brehm, J. M., & Amri, A. (2021). Ex situ and in situ conservation gap analysis of crop wild relative diversity in the Fertile Crescent of the Middle East. *Genetic Resources and Crop Evolution*, *68*(2), 693–709. https://doi.org/10.1007/s10722-020-01017-z

Zhang, K., Yao, L., Meng, J., & Tao, J. (2018). Maxent modeling for predicting the potential geographical distribution of two peony species under climate change. *Science of the Total Environment*, *634*, 1326–1334. https://doi.org/10.1016/j.scitotenv.2018.04.112

Zhang, L., Zhu, L., Li, Y., Zhu, W., & Chen, Y. (2022). Maxent modelling predicts a shift in suitable habitats of a subtropical evergreen tree (*Cyclobalanopsis glauca* (Thunberg) oersted) under climate change scenarios in China. *Forests*, *13*(1), 126. https://doi.org/10.3390/f13010126

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Area under the curve (AUC) curves for the six wild lentil species.

Figure S2. Prediction of potentially suitable habitat for *Lens culinaris* subsp. *odemensis* under current and future climate change scenarios SSP2-4.5 and SSP5-8.5 in 2050 and 2070.

Figure S3. Prediction of potentially suitable habitat for *Lens ervoides* under current and future climate change scenarios SSP2-4.5 and SSP5-8.5 in 2050 and 2070.

Figure S4. Prediction of potentially suitable habitat for *Lens lamottei* under current and future climate change scenarios SSP2-4.5 and SSP5-8.5 in 2050 and 2070.

Figure S5. Prediction of potentially suitable habitat for *Lens nigricans* under current and future climate change scenarios SSP2-4.5 and SSP5-8.5 in 2050 and 2070.

Figure S6. (a) Species Richness Map of Wild Lentil Species according to the IUCN criteria B: Low richness region represented by 2 species (blue), while high richness region represented 5 species (brown), (b) proportion (in %) of threatened species.

Figure S7. Response curves of the Mean Temperature of the Driest quarter (BIO9) predictor used in the ecological niche model of the six wild lentil species.