Tropical Plants

ARTICLE

Open Access

https://doi.org/10.48130/tp-0024-0045

*Tropical Plants* **2024**, in press

# The potential distribution of tree heath (*Erica arborea* L.) in Tigrai


## Authors

Daniel Hagos Berhe*, Amare Sisay Tefera, Tesfay Gidey, Abeba Nigussie Retta, Aklilu Negussie, ...

## Correspondence

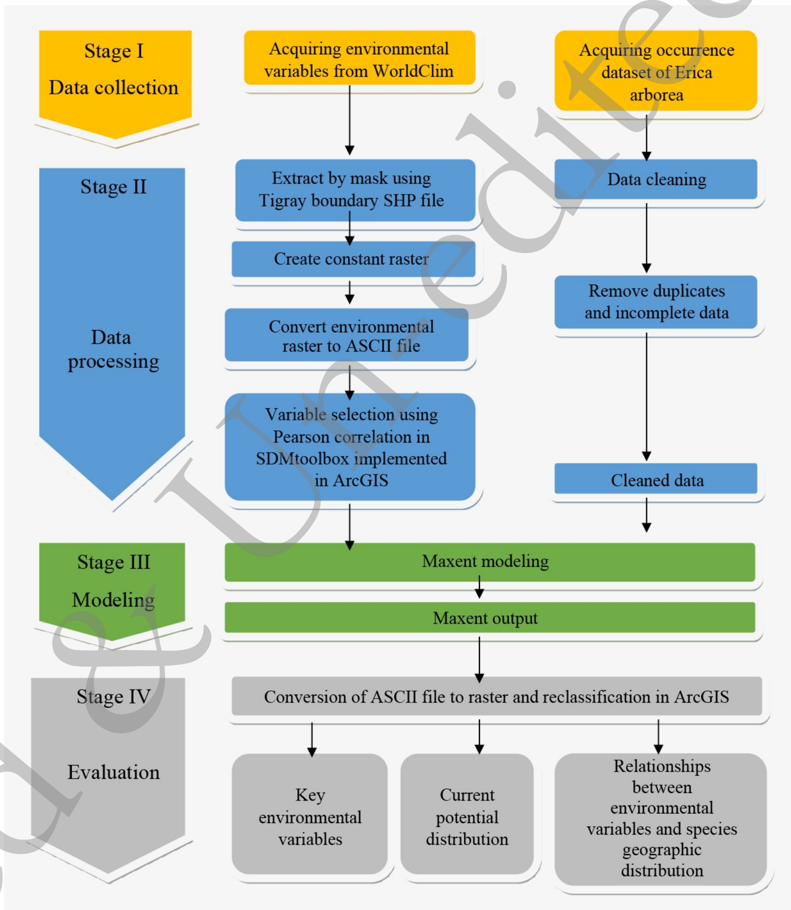
danielhgs829@gmail.com



## In Brief

Using 58 occurrence data points and selected environmental variables, the potential distribution of tree heath (Erica arborea L.) under two climatic scenarios and for two periods was modeled. Topographic and bioclimatic variables influenced the distribution range of E. arborea. Altitude, distance from the sea, aspect, precipitation of the warmest quarter, precipitation in the driest quarter, and precipitation in the wettest quarter were the most influential variables shaping Erica's distribution and suitable habitat.


## Graphical abstract






## Highlights

- Tree heath is one of the rare plant species facing a drastic population decline
- Maxent performance was excellent (AUC > 0.9) in predicting the potential distribution of tree heath
- The current potential area coincides with that modeled by Maxent and ArcGIS
- The distribution of E. arborea was highly associated with cold temperature (i.e. high altitude) and rainfall
- Under RCP8.5 in 2070, the suitable habitat range of Erica will shrink by 54%

**Citation:** Berhe DH, Tefera AS, Gidey T, Retta AN, Negussie A, et al. 2024. The potential distribution of tree heath (*Erica arborea* L.) in Tigrai. *Tropical Plants* https://doi.org/10.48130/tp-0024-0045

Tropical Plants

ARTICLE

Open Access

https://doi.org/10.48130/tp-0024-0045

*Tropical Plants* **2024**, in press

# The potential distribution of tree heath (*Erica arborea* L.) in Tigrai

Daniel Hagos Berhe[1*], Amare Sisay Tefera[1], Tesfay Gidey[1], Abeba Nigussie Retta[1,2], Aklilu Negussie[3], Emiru Birhane[2,4], Jan Nyssen[5], Paulo Alexandre Vieira Borges[6], Berihu Tesfamariam Zeratsion[7], Elena Kuzminsky[8] and Mariagrazia Agrimi[8]

[1] *University of Adigrat, P.O. Box 50, Adigrat, Ethiopia*
[2] *Department of Land Resources Management and Environmental Protection, Mekelle University, Mekelle, Ethiopia*
[3] *WeForest organisation, Addis Ababa, Ethiopia*
[4] *Norwegian University of Life Sciences (NMBU), Postboks 5003, INA, 1432, Ås, Norway*
[5] *Department of Geography, Ghent University, Krijgslaan 281(S8), 9000 Ghent, Belgium*
[6] *cE3c- Centre for Ecology, Evolution and Environmental Changes/Azorean Biodiversity Group, CHANGE – Global Change and Sustainability Institute, School of Agricultural and Environmental Sciences, University of the Azores, Rua Capitão João d´Ávila, Pico da Urze, 9700-042 Angra do Heroísmo, Azores, Portugal*
[7] *Ethiopian Forestry Development, Mekelle Centre, Mekelle, Ethiopia*
[8] *Department for Innovation in Biological, Agro-food and Forest System, University of Tuscia, Via S. Camillo de Lellis snc, 01100, Viterbo, Italy*
* Corresponding author, E-mail: danielhgs829@gmail.com

## Abstract

Tree heath (*Erica arborea* L.) is a rare and endangered native tree species that is facing an incessant population decline due to climatic and anthropogenic factors. The objective of this study was to analyse the impacts of future climate change on the potential distribution of the species in the alpine areas of Tigrai. A species distribution modelling using Maxent was employed to predict the potentially suitable habitat for the species under two future climatic scenarios. The model was constructed using 58 sets of presence data collected from five main forest areas of the region and 11 environmental predictors. The results revealed that altitude, precipitation in the warmest quarter, distance from the sea, aspect, precipitation in the driest quarter and precipitation in the wettest quarter were the main factors influencing the distribution of *E. arborea*. The distribution of *E. arborea* was highly associated with cold temperature (high elevation) and rainfall. *E. arborea* is sensitive to temperature fluctuations (bio7). The current suitable habitats of *E. arborea* were restricted within 2097 km$^2$. The highly suitable habitats for future distribution were the Irob, Atsibi, Emba Alaje, Endamokhoni, Ofla and Tsegede highlands of Tigrai. Under RCP8.5 in 2070, the suitable habitat range of *Erica* will shrink by 54%. Therefore, in situ and ex situ conservation interventions should be introduced to save the rare species in the Tigrai highlands.

**Citation:** Berhe DH, Tefera AS, Gidey T, Retta AN, Negussie A, et al. 2024. The potential distribution of tree heath (*Erica arborea* L.) in Tigrai. *Tropical Plants* https://doi.org/10.48130/tp-0024-0045

## Introduction

Tropical high mountain ecosystems host important biodiversity hotspots[1,2]. These precious ecosystems are under threat of rapid biodiversity loss which is a global concern[2−4]. Globally, 20% of plant species are at a brink of extinction due to both anthropogenic and natural factors[4]. Climate change[3,5], habitat fragmentation[3,4], invasion of alien species[6−10], pathogens[4], overexploitation[3,4,11] and a booming human population[3,4] are major risk factors contributing to species extinction.

Tree heath (*Erica arborea* L.), referredto hereafter as *Erica*, (family *Ericaceae*) is a much-branched evergreen shrub or small tree up to 12 m tall[12,13]. It is native to East and North Africa, southern and Eastern Europe and a few countries in West Asia[14,15]. It grows on dry rocky areas with shallow soils[15]. In the African highlands, it is found between 1900 m to 4000 m usually as a distinct vegetation belt above Afromontane forests (*Ericaceous* Belt), and also in clearings within forested areas. Above 3500 m, it is found as a small bush[1,16] while in the Mediterranean it is found in evergreen shrub lands or maquis along the coasts up to more than 1100 m[13].

*Erica* is used for various purposes. For instance, it produces copious pink pollen and abundant nectar throughout most of the year. This makes *Erica* one of the most important honey sources at higher altitudes[17] as it fetches premium prices and higher monetary returns especially for the Irob communities in Tigrai, Ethiopia (personal communication). *Erica* also produces lignotubers that are highly treasured for making briar pipes[13] and dice[17]. In traditional medicine, the smoked parts of the species are used to fumigate houses against contagious diseases[17]. Branches and wood are popular for firewood and charcoal production[18]. It is also used as fodder and for live fences[15].

*Erica* is experiencing a drastic population decline throughout its native range. Globally, though there is no known population information[14,19], the species is listed as Vulnerable in Andorra and Bulgaria and as a Least Concern within Europe[14]. Likewise, WeForest[20] reported that *Erica* was extinct in 4 villages out of 11 villages from the dry Afromontane Desa'a forest in Tigrai. Similarly, in the Peloritani Mountains of Italy, nearly 5,800 ha of *Erica*-dominated shrub lands have vanished[13]. These problems were associated with farmland expansion, wildfire, free grazing, new settlements, illegal logging and charcoal making[18,20,21]. In addition, climate change has become a clear threat to the distribution, growth, and survival of many indigenous plant species particularly in recent years[22].

Most tree species distributions are affected by climate change[23−27]. To survive the effects of climate change, species in the tropics may be pushed to higher elevations by effectively shrinking their distributions[28] or migrating to new suitable habitats[25]. Among the species most vulnerable to reductions in suitable habitat due to climate change are those that are adapted to Afroalpine forest ecosystems[2,23]. These ecosystems host many rare, endangered and flagship species[23].

Previous studies on *Erica* focused on dendrochronology[21], phylogeography inferred from AFLPs and plastid DNA[12], the effects of fire and grazing[29,30] and tree heath utilization[13]. To the best of our knowledge, studies focusing on the ecological niche (distribution pattern with climate change) of *Erica* using species distribution models (SDMs) and ArcGIS and how global climate change might affect Erica's distribution in the future are limited. However, to mitigate the effects of climate change, it is possible to effectively target conservation strategies by modelling species distributions and identifying areas where sensitive species exist or are likely to exist[2,26]. Because effective conservation planning requires a comprehensive understanding of the relationships of species to their environment under changing climatic conditions[31,32].

SDMs constitute the most common class of models across ecology, evolution and conservation[33] in view of supporting species conservation and management interventions. Among the many SDM algorithms, the open-source software Maxent (https://biodiversityinformatics.amnh.org/open_source/maxent/) has proven powerful when modelling rare and endangered species[11,26,34] using presence-only occurrence data[26,35]. Because SDM is valuable for anticipating conservation regions (particularly zones for species protection, restoration, translocation, and reintroductions) and for addressing questions about niche evolution trends[2]. This is the first study to use a niche modelling approach to model the distribution of *Erica* and the resulting outputs of our study may provide valuable information for conservation, management and research of the species. Hence, this study aimed to (1) predict the current potential distribution of *Erica* in its native distribution ranges, (2) identify the environmental variables associated with the *Erica* habitat distribution and (3) assess the potential impact of climate change on the future distribution of the species.

## Methods

### Study area

The study area was located in the mountain chain highlands of Tigrai (Fig. 1). Tigrai exhibits agroecological diversity, characterized by variations in temperature, rainfall, topography, soil characteristics, vegetation cover and other natural resources[22]. As such, it is part of the Eastern Afromontane biodiversity hotspot[18,36] due to its natural landscape and diversified agroecology[22]. The highlands of Tigrai is home to the remnant dry Afromontane forests of Asimba Natural Forest (14°15'–14°30' N and 39°30'–39°45' E), Desa'a National Forest Priority Area (13°20'–14°10' N and 39°32'–39°55 E), Hugumburda Grat Kahsu National Forest Priority Area (12°33'–12°42' N and 39°30'–39°39' E), Wujig Mahgo Waren Forest (12°47'–13°02' N and 39°26'–39°39' E) and the church forests of Michael Abeda and Tabotat. The topographies of the study sites are characterised by a mountain plateau with undulating terrain interspersed with low situated valleys, hills and flatlands. The amount of

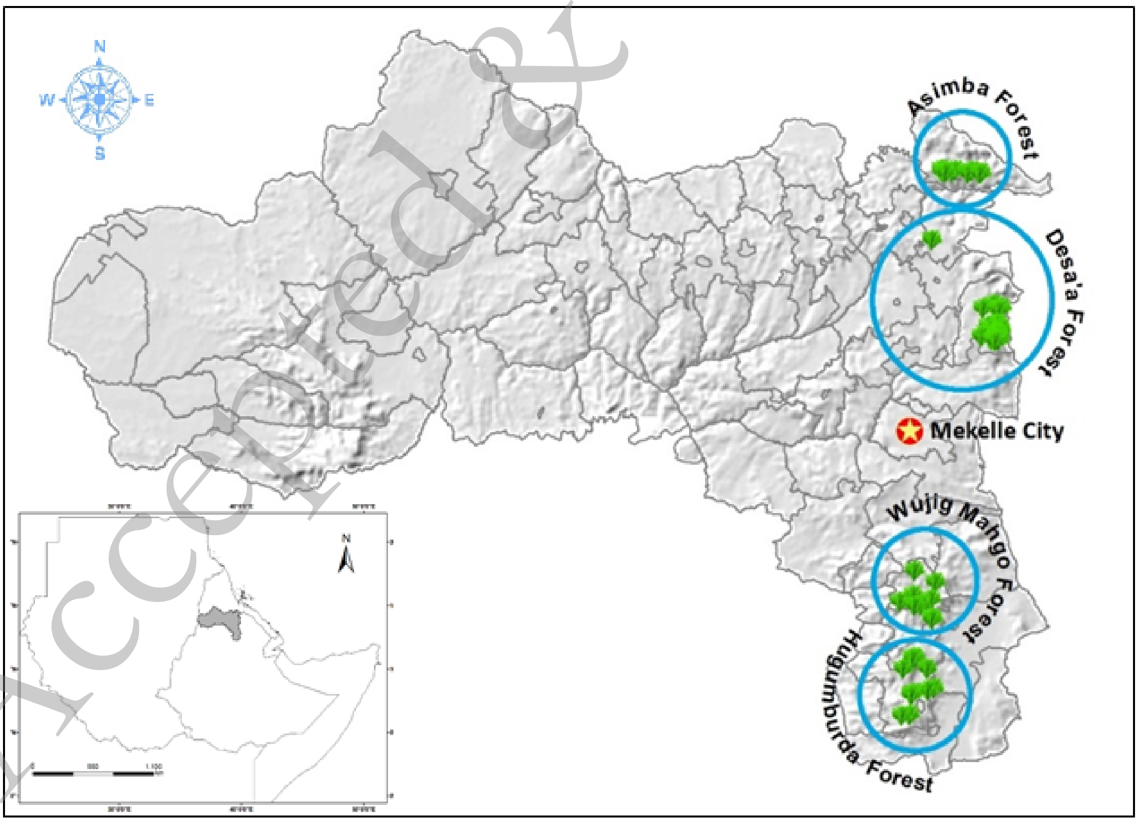



**Fig. 1** Location of the study area in relation to the Horn of Africa. The blue circles refer to the regional forest areas where the occurrence points were taken. The green areas are used to indicate to forest stands (trees).

rainfall for Asimba and Desa'a ranges from 116.3 to 230.0 mm during the main rainy season while the temperature range is 7.5 to 22.6 °C. Hugumburda Grat Kahsu, Wujig Mahgo Waren, Michael Abeda and Tabotat receives mean annual rainfall ranging between 350 mm and more than 1,000 mm, mean minimum annual temperature range between 6.3 and 20.6 °C and the mean maximum annual temperature ranges from 15.1 to 29.7 °C.

## Target species and occurrence data

The target species for the species distribution modelling simulation was the rare native[18,37] tree *Erica* (Figure 2). It is among the rare species (IVI of 0.26–0.58) in the highlands of Tigrai with poor seedling regeneration[38]. The species has experienced local extinction mainly due to logging for its good fuelwood[37] and charcoal production in recent years following the genocidal war and due to climatic factors.

For modelling of the species, we collected presence-only occurrence data for 89 species from the study forests (Figure 2) and from WeForest records. These occurrence data were converted to decimal degrees and then cleaned by removing outliers and duplicates in each 1 km × 1 km grid at the scale of the bioclimatic variables used[11]. To eliminate duplicated occurrence points and minimize the potential influence of environmental variations on model accuracy, we used the Python-based GIS toolkit SDM toolbox , implemented in ArcGIS[22,39]. Finally, 58 occurrence data points were retained and were used to determine the species distribution using Maxent.

## Predictor environmental variables

Twenty-three environmental variables consisting of 19 bioclimatic variables and 4 topographic variables) were downloaded from different sources to simulate the distributions of the species. The 19 climatic variables and altitude data were retrieved from the World Climate Database (http://www.worldclim.org) at a spatial resolution of 1 km. From the altitude data, aspect and slope were extracted while the distance from the sea was calculated as the shortest distance from the shoreline using ArcGIS 10.8.1.

To reduce multicollinearity among the 19 bioclimatic variables and the 4 topographic variables, highly correlated variables ($r \geq |0.85|$ Pearson correlation coefficient) were eliminated from further models[47]. This reduction in predictor variables resulted in the inclusion of eleven variables in the models (Table 1 and Supplementary Table S1). The selected variables included temperature annual range, annual precipitation, precipitation in the driest month, precipitation in the wettest quarter, precipitation in the driest quarter, precipitation in the warmest quarter, precipitation in the coldest quarter, altitude, slope, aspect and distance from the sea (Table 1).

## Future climate scenario

We used the climate data obtained from the WorldClim to model the current and future potential distributions of *Erica*. The current climate data represent the average for the years 1950 – 2000. Future climate projections were developed for the years 2050 (2041–2060) and 2070 (2061–2080). Both current and future climate data were obtained from a global atmospheric circulation model, the Community Climate System Model version 4 (CCSM4)[40−42] and two representative concentration pathways (RCPs). RCP4.5 (intermediate GHG emission hypothesis) and RCP8.5 (maximum GHG emission hypothesis) were considered in our study for future species distribution predictions. These RCP scenarios represent climate conditions under which radiative forcing is projected to increase by 4.5 and 8.5 Watts per square meter ($Wm^{-2}$) by the year 2100[28,40]. In other words, the RCP4.5 scenario represents a pathway in which global greenhouse emissions gradually increase, followed by a decline after 2030 while the RCP8.5 scenario represents a 'baseline' scenario pathway with no climate mitigation target and an increase in emissions throughout the century[43].

## Modelling approaches

To predict the potential distribution of *Erica,* Maxent 3.4.1 was used[44,45]. As input, we loaded the selected uncorrelated environmental variables and the species occurrence data of *Erica* into the Maxent model. To simulate the model, 75% of the occurrence data were used for calibration (training) and the remaining 25% were used for validation[46]. Furthermore, to assess the relative contribution of each variable to the model, the Jackknife test[44] and the area under the curve (AUC) of the receiver operating characteristic curve (ROC) were used[11,47,48]. The AUC values were categorized as invalid (0.5 – 0.6), poor (0.6 – 0.7), average (0.7 – 0.8), good (0.8 – 0.9) or excellent (0.9 – 1)[47]. Thus, prediction results can be adopted when the AUC is 0.7 – 0.9 and when the AUC > 0.9, indicating that the prediction results are very accurate[48].

Finally, using the 10$^{th}$ percentile training presence logistic threshold as the cut-off point, we developed a habitat suitability index divided into five classes. The classes are 0.0–0.2 (unsuitable), 0.2–0.4 (low suitable), 0.4–0.6 (suitable), 0.6 – 0.8 (highly suitable) and 0.8–1.0 (exceptionally suitable)[26,49]. Based on this classification, an area less than 0.2 is considered as unsuitable while areas between 0.2 and 1 are considered as suitable and areas above 0.6 are considered as optimally suitable[47]. We also calculated the total extent of occurrence (EOO) of the species based on the procedure outlined in IUCN[50]. This


**Fig. 2** *Erica arborea* L. and its landscape around Embahasti – Alaje (a) and an *Erica* patch on the northern slopes of the Dabba Selama peak in Dogu'a Tembien (b).

**Table 1.** Environmental variables used for distribution modelling of *Erica* in Tigrai

| Label | Environmental variables | Factor | Unit |
|---|---|---|---|
| bio1 | Annual mean temperature | 10 | °C |
| bio2 | Mean diurnal range (mean of monthly (max temp – min temp)) | 10 | °C |
| bio3 | Isothermality (bio2/bio7)*(100) | 100 | – |
| bio4 | Temperature seasonality (standard deviation*100) | 100 | % |
| bio5 | Max temperature of warmest month | 10 | °C |
| bio6 | Min temperature of coldest month | 10 | °C |
| bio7 | Temperature annual range (bio5-bio6) | 10 | °C |
| bio8 | Mean temperature of wettest quarter | 10 | °C |
| bio9 | Mean temperature of driest quarter | 10 | °C |
| bio10 | Mean temperature of warmest quarter | 10 | °C |
| bio11 | Mean temperature of coldest quarter | 10 | °C |
| bio12 | Annual precipitation | 1 | mm |
| bio13 | Precipitation of wettest month | 1 | mm |
| bio14 | Precipitation of driest month | 1 | mm |
| bio15 | Precipitation of seasonality (coefficient of variation) | 100 | % |
| bio16 | Precipitation of wettest quarter | 1 | mm |
| bio17 | Precipitation of driest quarter | 1 | mm |
| bio18 | Precipitation of warmest quarter | 1 | mm |
| bio19 | Precipitation of coldest quarter | 1 | mm |
| | Altitude | 1 | m a. s. l |
| | Aspect | 1 | Degree |
| | Distance from sea | 1 | km |
| | Slope gradient | 1 | % |

• Those highlighted in bold refer to the selected environmental variable for the modelling; • Factor refers to the scale by which the environmental variable is multiplied for ease of storage in the raster.

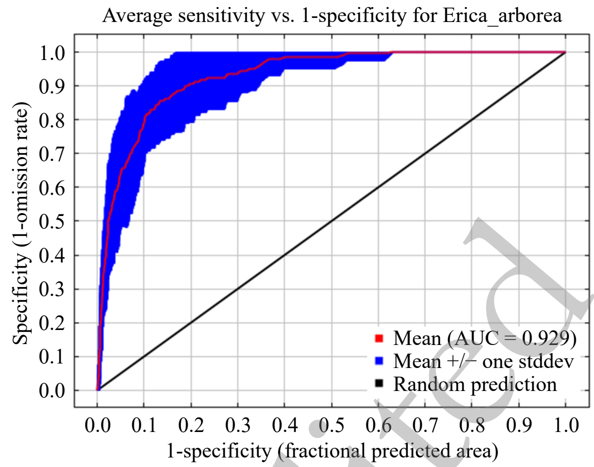



**Fig. 3** Model performance ROC curve of the reconstructed Maxent model under current climatic simulation

approach considers 0.5 as the threshold above which the species is most likely present[51].

## Results

### Model performance

The Maxent model performed well in predicting the potential distribution of *Erica* in its native range (Figure 3). Except for RCP8.5 in 2070, which had an AUC value of 0.888 ± 0.085, all the AUC values (0.929 ± 0.039 under the current scenario, 0.923 ± 0.031 under RCP4.5 and 0.912 ± 0.036 under RCP8.5 in 2050 and 0.901 ± 0.043 under RCP4.5 in 2070) were > 0.9 indicating that the model's high accuracy with and its high discriminative ability.

### Variable importance and contribution

The three most important variables for predicting the current potential distribution of *Erica,* with more than 86% contribution to the model, were altitude, precipitation of the driest quarter and distance from the sea (Fig. 4 & Table 2). Under RCP4.5 in 2050, the variables altitude (56.9%), precipitation of the driest quarter (13.5%), temperature annual range (10.4) and precipitation of the driest month (7.4%) contributed 88.2% to the model. Under RCP8.5 in 2050, altitude (49%), distance from the sea (11.7%), temperature annual range (11.3%) and precipitation of driest quarter (8.9) combined contributed 80.9% to the model. Under RCP4.5 in 2070, the variables altitude (56.1%), precipitation of the driest quarter (17.7%), precipitation of the warmest quarter (12.3%) and distance from the sea (6.4%) contributed 80.9% to the model. Under RCP8.5 in 2070, the variables altitude (43.7%), precipitation of coldest quarter (15.8%), precipitation of driest month (10.4%), distance from the sea (12.6%) and aspect (5.7%) contributed 88.2% to the model (Table 2).

Topography-related variables followed by the precipitation-related variables had the highest (52.8% and 34.6%, respectively) contribution to the model in predicting the current distribution of *Erica*. Among the topographic variables, altitude (29.6%) contributed the most to the model while precipitation of the warmest quarter (28.8%) contributed the most among the precipitation variables. The temperature-related variable, temperature annual range, contributed the least to the model. The environmental variable with the highest gain when used in isolation is precipitation of the warmest quarter (Figure 4), which therefore appears to have the most useful information by itself. The environmental variable that decreases the gain the most when it is omitted is altitude (Figure 4), which therefore appears to have the most information that is not present (i.e. temperature) in the other variables.

### Response of *Erica* to environmental variables

Suitable habitats of *Erica* increase with an increase in altitude. Suitable altitude for the species was in the range of 2,357–3,750 m with optimal altitude at 3,750 m while habitats with altitude of less than 2,357 m are unsuitable for *Erica*. Moreover, both sloppy (10%–70%) and flat (0–10%) and North and northwest-facing areas are suitable habitats for *Erica* with Northeast facing optimally suitable habitats. Habitats at a distance of 55.5–288.6 km from the sea with the best at 55.5 km are suitable habitats for *Erica*. *Erica* revealed habitat suitability inversely proportional to the increase of the temperature annual range, indicating a high sensitivity to large fluctuations in temperature.

Suitable habitats of *Erica* also increase with increasing annual precipitation. Optimal precipitations were at 600 mm (550–600 mm) for areas around Desa'a and Asimba and at 950 (850–950 mm) for areas in south Tigrai (Tabotat, Michael Abeda, Alaje and Ofla). Areas with precipitation (3–29 mm) in the driest month, precipitation (200–620 mm) in the wettest quarter, precipitation (16–140 mm) in the driest quarter, precipitation (120–360 mm) in the warmest quarter and precipitation (15–250 mm) in the coldest quarter are suitable habitats for *Erica*. Habitats with precipitation in the driest month (< 3 mm), precipitation of the driest quarter (< 16 mm) and precipitation

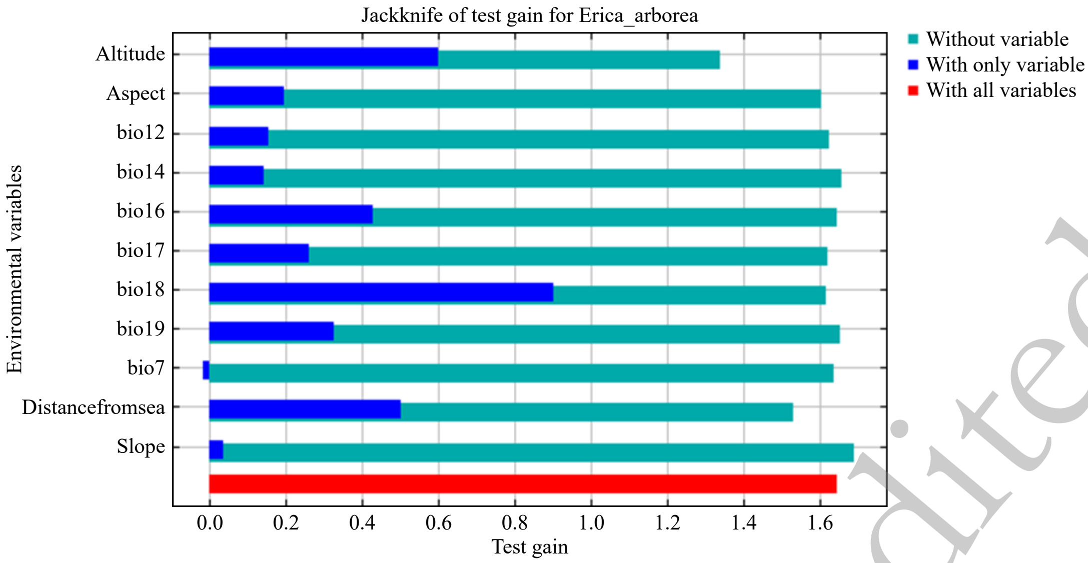



**Fig. 4** Jackknife analysis of the importance of environmental variables in modelling the distribution of *Erica*

**Table 2.** Estimates of relative contributions and permutation importance of the predictor environmental variables to the SDMs.

| Variables | Current | | Climatic scenario 2050 | | | | Climatic scenario2070 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | RCP4.5 | | RCP8.5 | | RCP4.5 | | RCP8.5 | |
| | PC (%) | PI (%) | PC (%) | PI (%) | PC (%) | PI (%) | PC (%) | PI (%) | PC (%) | PI (%) |
| Altitude | 29.6 | 45.2 | 27.3 | 56.9 | 32.2 | 49 | 33.8 | 56.1 | 29.1 | 43.7 |
| Aspect | 9.5 | 3.3 | 9.4 | 3.7 | 10.1 | 4.5 | 10.6 | 3.1 | 9 | 5.7 |
| bio12 | 2.1 | 1.9 | 1.4 | 1.7 | 1.6 | 4 | 0.5 | 1 | 1.7 | 4 |
| bio14 | 0.2 | 0.7 | 1.2 | 7.4 | 0 | 0.6 | 0.8 | 0.9 | 1.3 | 10.4 |
| bio16 | 5.8 | 0.1 | 6.7 | 0.2 | 3.1 | 0.1 | 3.1 | 0 | 5.7 | 1.3 |
| bio17 | 7.7 | 33.1 | 3.7 | 13.5 | 2.1 | 8.9 | 6.8 | 17.7 | 0.1 | 1 |
| bio18 | 28.8 | 3.1 | 1.8 | 0.5 | 22.2 | 5.7 | 25.6 | 12.3 | 15.8 | 1.8 |
| bio19 | 0.5 | 3 | 1.2 | 0.8 | 1.4 | 2 | 1.5 | 0.2 | 19.8 | 15.8 |
| bio7 | 0.6 | 0.1 | 13.2 | 10.4 | 12.4 | 11.3 | 0.8 | 0.6 | 4.3 | 0.5 |
| Distance | 13.7 | 8.3 | 1 | 1.2 | 12.9 | 11.7 | 14.6 | 6.4 | 11.3 | 12.6 |
| Slope | 1.5 | 1.2 | 33.1 | 3.7 | 1.9 | 2.3 | 2.1 | 1.7 | 1.8 | 3 |

PC – Percent Contribution, PI – Permutation Importance, Distance – Distance from the sea

(< 120 mm) in the warmest quarter and precipitation (< 15 mm) in the coldest quarter are unsuitable habitats for *Erica*.

## Predicted current potential distribution of *Erica*

The total potential suitable habitat for *Erica* in Tigrai is 2097 km$^2$, accounting for 9.12% of Tigrai's highland area (Table 3 and Figure 5), as *Erica* is supposed to grow at >1800 m. Its EOO is 714 km$^2$. In addition, 21.22% (445 km$^2$) of the total area was optimally suitable habitat (>0.6), 23.80% (499 km$^2$) was suitable (0.4 – 0.6) and 54.98% (1153 km$^2$) was a low suitability (0.2 - 0.4) habitat. The unsuitable habitat covers 12855 km$^2$, accounting for 55.97% of the highland area. The exceptionally suitable area is confined to the highlands of Tsegede, Welqait, Irob, Ganta Afeshum, Atsibi, Ofla and Emba Alaje while the highly suitable areas are found in the districts Tsegede, Welqait, Irob, Subha Saesie, Tsaeda Emba, Atsibi, Tsirae Wenberta and Ofla districts in Tigrai, Ethiopia. Suitable habitats are found in Tsegede, Irob Subha Saesie, Tsaeda Emba, Atsibi, Tsirae Wenberta and Ofla. The less suitable habitat covers a large area and is found in the Welqait, Tsegede, Awra, Irob, Gulo Mekeda, Ganta Afeshum, Subha Saesie, Tsaeda Emba, Atsibi, Tsirae Wenberta, Ofla, Raya Alamata, Raya Azebo and Emba Alaje districts.

## Predicted future potential distribution of *Erica*

The potential distribution of *Erica* under future climate change scenarios revealed various patterns (Figure 8). The predicted future potential distribution of *Erica* showed that there was a total gain in both the suitable (+303 km$^2$) and unsuitable (+472 km$^2$) habitats (Table 3 and Figure 6) under RCP4.5 in 2050 when compared to the current distribution. Under RCP8.5 in 2050, there would be an increase in unsuitable habitat (+1123 km$^2$), accompanied by a decrease in suitable habitat (–209 km$^2$). Under RCP4.5 and RCP8.5 by 2070, the unsuitable habitat would increase by 946 km$^2$ and 382 km$^2$ respectively, while the suitable habitat would increase by only 0.09% (2 km$^2$) for RCP4.5 and shrink by 1099 km$^2$ under RCP8.5. In addition, *Erica* has EOO values of 418 km$^2$, 1273 km$^2$, 73 km$^2$ and 913 km$^2$ under RCP4.5 in 2050, RCP8.5 in 2050, RCP4.5 in 2070 and RCP8.5 in 2070, respectively.

# Discussions

## Model evaluation

The accuracy of the Maxent model outputs were excellent with high (AUC > 0.9 for both training and testing) discrimina-

**Table 3.** Predicted changes (km$^2$) in *Erica* ranges in the 2050s and 2070s under two climatic scenarios (RCP4.5 and RCP8.5) compared with the potential current distribution.

| Suitability category | Current | Future scenario 2050 | | Future scenario 2070 | |
|---|---|---|---|---|---|
| | | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Unsuitable | 12855 | 13327 (+472) | 13978 (+1123) | 11909 (−946) | 12473 (−382) |
| Low suitable | 1153 | 1321 (+158) | 838 (−315) | 1166 (+13) | 420 (−733) |
| Suitable | 499 | 588 (+89) | 490 (−9) | 513 (+14) | 171 (−328) |
| Highly suitable | 267 | 315 (+48) | 274 (+7) | 308 (+41) | 142 (−125) |
| Exceptionally suitable | 178 | 186 (+8) | 286 (108) | 112 (−66) | 265 (87) |

(+) refers to gain and (-) refers to loss in range areas (km$^2$).

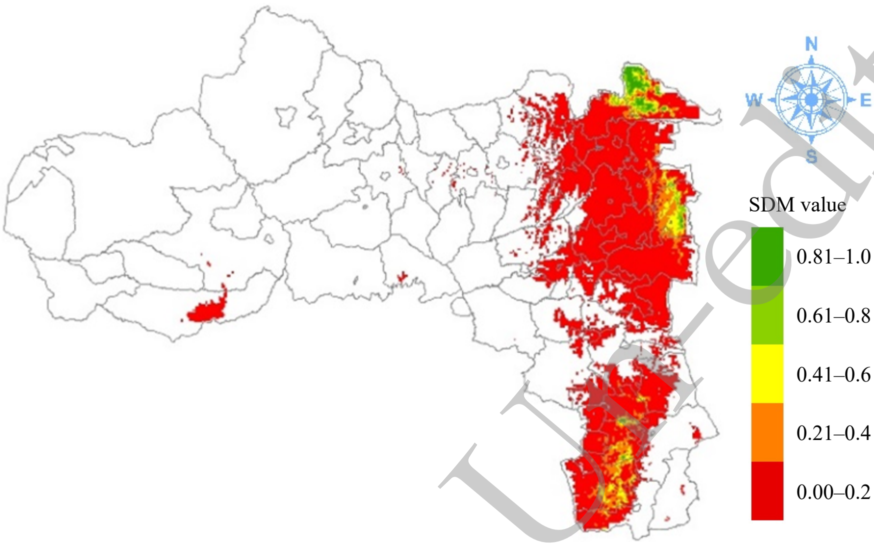



**Fig. 5** Predicted current potential distribution of Erica in Tigrai

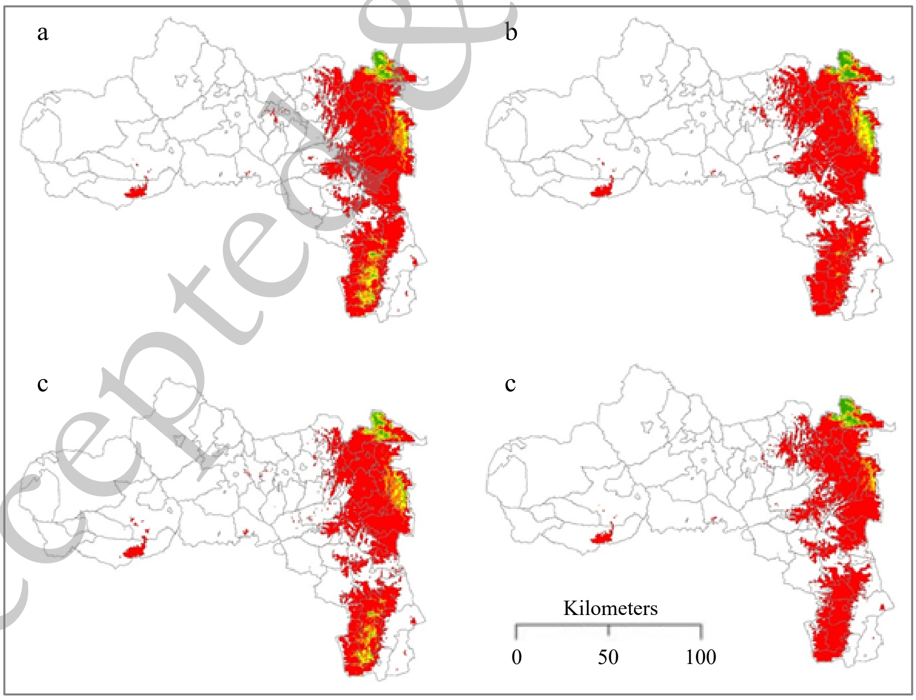



**Fig. 6** Predicted future average potential distribution model of *Erica* (a) 2050 RCP4.5 (b) 2050 RCP8.5 (c) 2070 RCP4.5 (d) 2070 RCP8.5.

tive ability, except under RCP8.5 in 2070 with good performance, with an AUC of 0.95 for training and AUC of 0.88 for testing. Models with an AUC value above 0.90 are considered to have an excellent performance[9,48] while with an AUC value of

0.8 - 0.9 is indicative of the high precision[52] and, thus, are considered promising[9,43,52]. Moreover, our results are comparable to various studies done in the region using Maxent modelling approach[22,41,53–55] and other SDM approaches[23,39,56]. Our simulation results are reliable in terms of model evaluation thus could be used to simulate other similar highland species.

Species distribution models have proven valuable in filling gaps in our knowledge of species occurrences[57]. Many studies have demonstrated the usefulness of SDMs to determine ideal locations for species reintroduction and relocation[23,39,56,57]. However, there are certain limits to using SDMs, particularly when available data is insufficient for the modelling process to be effective[58]. Other critical shortcomings include sample size, positional uncertainty, and sampling bias and the species ecology[57]. For instance, including solely bioclimatic factors may lead to bias in the results because other factors such as human activities and dispersion restrictions also play important roles in determining such species' future ranges[58]. In this study, to improve the accuracy of the model, we have added additional environmental variables on top of the usual bioclimatic variables.

## Response of *Erica* to environmental variables

Environmental factors and climate change have a significant impact on how species disperse, migrate, evolve, adapt, and go extinct[2]. Topographic and bioclimatic variables influenced the distribution range and survival of *Erica* (Table 2,Figure 6). The six most influential variables with more than 95% cumulative contribution to the model were altitude, distance from the sea, aspect, precipitation of warmest quarter, precipitation in the driest quarter and precipitation in the wettest quarter. The importance of these variables suggest that the association of *Erica* with cold temperature (i.e. high altitude) and rainfall[12–14,21,29,30,59] and its sensitivity to temperature fluctuations (bio7)[1,12,14,21]. Our findings are in line with earlier studies on the species. A study on tree ring chronology, Jacob et al. (2020), found a statistically significant correlation ($p < 0.05$) between the growth of *Erica* and the minimum temperature in March and August and the correlation was able to explain 24% of the variation in tree growth. According to these authors, the minimum temperature in the growing season (August) controlled tree growth and warmer temperatures enhanced the growth of *Erica*. It was further elaborated that rainfall impeded tree growth under wet conditions and enhanced tree growth under dry conditions[21].

Altitude is an important environmental factor affecting the soil, vegetation, and microclimate of forests, the growth and distribution of plants[60]. Altitude along with aspect and slope are the three main topographic factors that control the distribution and patterns of species in mountain areas of East Africa[39,61]. Altitude was strongly correlated with temperature, and the distribution of *Erica* was strongly influenced by altitude (Figure 6). This result reinforces the findings of other species distribution modelling carried out other plant species on flora[4,11]. In Tigrai, marked variation in altitude results in a distinct spatial distribution of temperature and rainfall[62]. Aspect controls species distribution by inducing local variations in the temperature and precipitation of mountainous topographies[63] through effects on hydrological and solar energy regimes[61,63]. In our study, we found Northeast-facing habitats to be optimally suitable for *Erica* presumably due to cooler and wetter conditions in these areas.

Precipitation is the most decisive factor controlling species distribution in the drylands[34,61]. It is also assumed that the dry Afromontane forests trap moisture from the clouds or mist, which usually builds up along the escarpments[36]. Thus, distance from the sea is another factor influencing the distribution of *Erica* through its influence on the coverage of fog, clouds and mist, from the Red Sea coast to the North and the Indian Ocean coast to the East, which provides moisture to the mountainous area[34,36] where *Erica* grows. Moisture, held in cloud droplet form/fog, drifts inland with the prevailing wind inferring the importance of distance from the sea and aspect.

## Predicted current potential distribution of *Erica*

The current distribution of *Erica* and those simulated with the SDMs and with expert knowledge using ArcGIS are consistent (Figure 6 and Figure 7). With the SDM and ArcGIS, we found additional suitable habitats for *Erica* in the highlands of Tsegede, Welqait, Tselemti, Ganta Afeshum and Dogu'a Tembien, these habitats need verification. In Tsegede, Welqait and Tselemti, we expect that *Erica* is effectively present as these districts are part of the Semien Mountain massif where *Erica* forms the *Erica* treeline ecotone[12,21]. In Dogu'a Tembien, a small remnant Erica forest occupies the northern slopes near the top of the Dabba Selama Mountains[64]. The optimally suitable habitats were found around Asimba, Aiga, Desa'a, Emba Alaje, Endamokhoni and Ofla.

## Predicted future potential distribution of *Erica*

Climate change-induced warming is expected to impact plant diversity, abundance and distribution[1]. Compared to the extent of suitable habitat under current conditions, the distribution range of *Erica* showed a tended to shrink under future climatic scenarios, under RCP8.5 both in 2050 and in 2070 (Figure 6 and Table 3). Specifically, under RCP8.5 the range will shrink by 209 $km^2$ in 2050 and by 1099 $km^2$ in 2070. The large range reduction (up to 52.41%) in RCP8.5 suggests that climate change might threatened *Erica*. In contrast, under RCP4.5, our SDMs show that the range of *Erica* will expand by 303 $km^2$ in 2050 and 2 $km^2$ in 2070. Much of the range expansion will occur in the eastern and western zones of Tigrai, while the range contraction will occur in the southern zones of Tigrai. Taking the 0.2 logistic threshold as the cut-off point, we found evidence of an altitudinal range shift (from 1800 to 2357 m) but we did not find evidence indicating longitudinal or latitudinal range shift. An altitudinal range shift supports the hypothesis that "climate change is expected to result in altitudinal range shift and range contraction in East Africa"[1] while the absence of latitudinal and longitudinal range shifts supports the hypothesis "Nowhere to go"[28].

## Conservation intervention

*Erica* is facing multiple threats including inherent problems, anthropogenic and climatic. It has a narrow range, the *Erica* ecotone. The seeds are very tiny and difficult to collect. Its natural regeneration is low, and it is hampered by grazing, trampling and poor precipitation. Seedlings are less successful[15] at establishment. Moreover, the species is not among the priority species for reforestation and afforestation activities. The species is highly logged for charcoal and fuelwood. The habitat where it grows is under constant pressure from increasing population, free grazing, illegal logging, charcoal making and

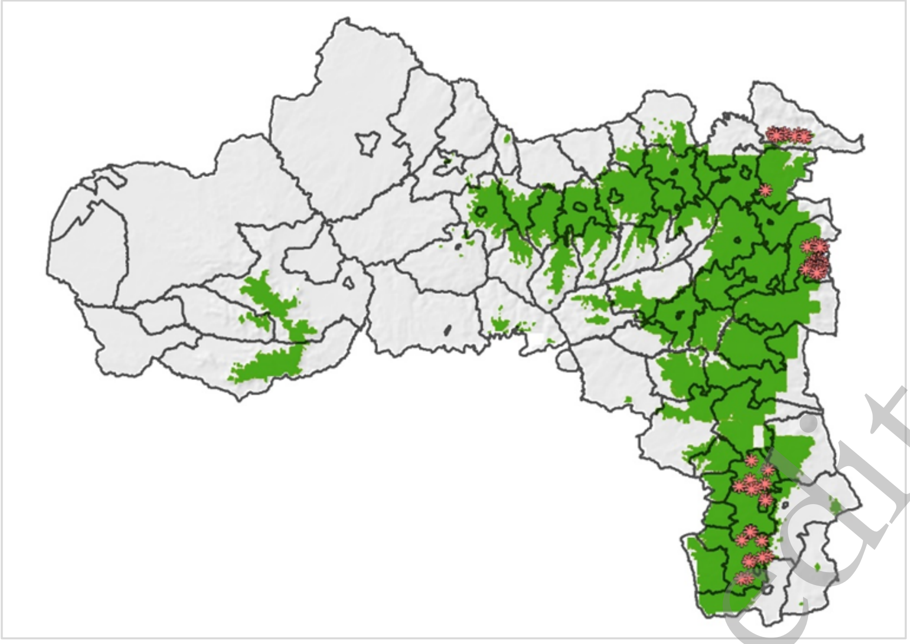


**Fig. 7** Suitability model of *Erica* predicted based on expert knowledge using five environmental variables and the current occurrence points. The green shaded area represents possible suitable areas for the growth of *Erica*. The red dots represent the actual presence data for *Erica*.

habitat conversion[53,65]. More importantly, its distribution will be reduced due to the impacts of climate change; putting it at the risk of extinction. Hence, in view of the drastic population decline and local extinctions, in situ and ex situ conservation of the species demands priority.

For its in-situ conservation, habitat protection and restoration should be prioritized because suitable habitats are prerequisites for species survival. Habitat restoration includes reintroduction of the species, enrichment planting, exclosing degraded lands to enhance natural regeneration, participatory soil and water conservation, watering, fencing, soil amendments and awareness creation. In addition, sustainable energy sources and improved stoves should be introduced. For its ex situ conservation, the establishment of botanical gardens, introducing planting in urban landscaping and use of biotechnology (micropropagation) are important. In numerus countries, also out of the strict territory of the plant (say, The Netherlands), *Erica* is grown as an ornamental plant[14]. Promoting it as an ornamental plant in private and public gardens in Tigray that fit with, the environmental requirements, particularly that are at least at higher elevations, would further support conservation of the species ex -situ by while creating job opportunities and generating income for gardeners. *Erica* is also a good source of nectar for bees and hence an opportunity to plant it would be appreciated in Tigray's home garden agroforestry, or as a spring off benefit from public plantations.

## Conclusion

We have successfully modelled and analysed the spatiotemporal distribution pattern and suitable habitat of *Erica* with SDMs and ArcGIS. We found highly suitable habitats in the districts of Irob (Aiga and Asimba Mountains), Atsibi (Desa'a), Emba Alaje (Wujig Mahgo Waren), Endamokhoni, and Ofla (Hugumburda) and in the highlands of Tsegede. These districts are areas with stable cold climates where *Erica* could form the *Erica* treeline ecotone. Altitude (29.6%), precipitation in the warmest quarter (28.8%) distance from the sea (13.7%), aspect (9.5%), precipitation of driest quarter (7.7%) and precipitation in the wettest quarter (5.8) were the main environmental variables shaping the distribution and suitable habitat for *Erica*. The suitable habitat range of *Erica* will shrink due to climate change. Hence, ex situ and in situ conservation of the plant is crucial.

## Author contributions

All authors have participated in the conception and design of the research, or in the formal analysis and interpretation of the data; drafting the article or revising it critically for important content and approval of the final version of the manuscript for publication.

## Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

## Acknowledgments

The authors acknowledge WeForest for provision of occurrence data and the Rufford Foundation for financial support (Code: 10f54f1).

## Conflict of interest

The authors declare that they have no conflict of interest.

**Supplementary information** accompanies this paper at (XXXXXX)

## Dates

Received 8 June 2024; Revised 22 October 2024; Accepted 24 October 2024; In press 7 November 2024

## References

1. Kidane YO, Jonas M, Beierkuhnlein C. 2019. Dead end for endemic plant species? A biodiversity hotspot under pressure. *Global Ecology and Conservation* 19:e00670
2. Mkala EM, Mwanzia V, Nzei J, Oulo MA, Oluoch WA, et al. 2023. Predicting the potential impacts of climate change on the endangered endemic annonaceae species in east africa. *Heliyon* 9:e17405
3. Alvey AA. 2006. Promoting and preserving biodiversity in the urban forest. *Urban Forestry and Urban Greening* 5:195−201
4. Adhikari D, Barik SK, Upadhaya K. 2012. Habitat distribution modelling for reintroduction of I*lex khasiana* Purk., a critically endangered tree species of northeastern India. *Ecological Engineering* 40:37−43
5. Sun J, Qiu H, Guo J, Xu X, Wu D, et al. 2020. Modeling the potential distribution of *Zelkova schneideriana* under different human activity intensities and climate change patterns in China. *Global Ecology and Conservation* 21:e00840
6. Nottingham CM, Glen AS, Stanley MC. 2019. Proactive development of invasive species damage functions prior to species reintroduction. *Global Ecology and Conservation* 17:e00534
7. Mader D, Dasgupta R, Kumar P, Johnson BA. 2020. Citizen science and invasive alien species: An analysis of citizen science initiatives using information and communications technology (ICT) to collect invasive alien species observations. *Global Ecology and Conservation* 21:1−14
8. Magro AA, Humberto M, Magro AA, Leandro C, Cordeiro DO, et al. 2019. Predicting the potential hybridization zones between native and invasive marmosets within Neotropical biodiversity hotspots. *Global Ecology and Conservation* 20:e00706
9. Yan H, Feng LLL, Zhao Y, Feng LLL, Wu D, et al. 2020. Prediction of the spatial distribution of *Alternanthera philoxeroides* in China based on ArcGIS and MaxEnt. *Global Ecology and Conservation* 21:1−15
10. Banerjee AK, Mukherjee A, Guo W, Ng WL, Yelin H. 2019. Combining ecological niche modeling with genetic lineage information to predict potential distribution of *Mikania micrantha* Kunth in South and Southeast Asia under predicted climate change. *Global Ecology and Conservation* 20:e00800
11. 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
12. Gizaw A, Kebede M, Nemomissa S, Ehrich D. 2013. Phylogeography of the heathers Erica arborea and E. trimera in the afro-alpine 'sky islands' inferred from AFLPs and plastid DNA sequences. *Flora* 208:453−463
13. La Mantia T, Giaimi G, Salvatore D, Mela L, Pasta S. 2007. The role of traditional *Erica arborea* L. management practices in maintaining northeastern Sicily's cultural landscape. *Forest Ecology and Management* 249:63−70
14. Harvey-Brown Y, Barstow M 2017. *Erica arborea*: The IUCN Red List of Threatened Species 2017. 8235: 1−8
15. Azene BT 2007. Useful trees and shrubs of Ethiopia: Identification, Propagation and Management for 17 Agroclimatic Zones. RELMA in ICRAF Project, Nairobi
16. Kindt R, Breugel P Van, Lillesø JB, Bingham M, Demissew S. 2011. Potential natural vegetation of eastern Africa. Volume 4: Description and tree species composition for bushland and thicket potential natural vegetation types. Forest & Landscape Denmark University of Copenhagen
17. Fichtl R, Adi A. 1994. Honeybee Flora of Ethiopia. Margraf Verlag
18. Aynekulu E, Aerts R, Moonen P, Denich M, Gebrehiwot K, et al. 2012. Altitudinal variation and conservation priorities of vegetation along the Great Rift Valley escarpment, northern Ethiopia. *Biodivers Conserv* 21:2691−2707
19. Vivero JL, Kelbessa E, Demissew S. 2005. The Red List of Endemic Trees and Shrubs of Ethiopia and Eritrea. Fauna & Flora International, Cambridge, UK
20. WeForest. 2018. The Great Rift Valley Dry Afromontane: Desa'a State Forest Management Plan. WeForest-Ethiopia, Mekelle, Tigrai, Ethiopia
21. Jacob M, Ridder M De, Vandenabeele M, Asfaha T, Nyssen, J. 2020. The Response of *Erica arborea* L. Tree Growth to Climate Variability at the Afro-alpine Tropical Highlands of North Ethiopia. *Forests* 11:1−14
22. Gebremedhn H, Gebrewahid Y, Haile GG, Hadgu G, Atsbha T, et al. 2024. Projecting the impact of climate change on honey bee plant habitat distribution in Northern Ethiopia. *Scientific Reports* 1−16. https://doi.org/10.1038/s41598-024-66949-3
23. Yebeyen D, Nemomissa S, Hailu BT, Zewdie W. 2022. Modeling and Mapping Habitat Suitability of Highland Bamboo under Climate Change in Ethiopia. *Forests* 13:1−16
24. Wan J, Mbari NJ, Wang S, Liu B, Mwangi BN, et al. 2020. Modeling impacts of climate change on the potential distribution of six endemic baobab species in Madagascar. *Plant Diversity*. https://doi.org/10.1016/j.pld.2020.07.001
25. Noulekoun F, Chude S, Zenebe A, Birhane E. 2016. Climate Change Impacts on *Faidherbia albida* (Delile) A. Chev. Distribution in Dry Lands of Ethiopia. African Journal of Ecology 233−243. https://doi.org/10.1111/aje.12345
26. Qin A, Liu B, Guo Q, Bussmann RW, Ma F, et al. 2017. Maxent modeling for predicting impacts of climate change on the potential distribution of *Thuja sutchuenensis* Franch. *, an extremely endangered conifer from southwestern China. Global Ecology and Conservation* 10:139−146
27. Urbani F, Alessandro PD, Biondi M 2017. Using Maximum Entropy Modeling (MaxEnt) to predict future trends in the distribution of high altitude endemic insects in response to climate change. *Bulletin of Insectology* 70: 189−200
28. Birhane E, Tadesse K, Tadesse T 2020. Vulnerability of baobab (*Adansonia digitata* L. ) to human disturbances and climate change in western Tigray, Ethiopia : Conservation concerns and priorities. 22 https://doi.org/10.1016/j.gecco.2020.e00943
29. Johansson MU, Fetene M, Malmer A, Granström A. 2012. Tending for Cattle: Traditional Fire Management in Ethiopian Montane Heathlands. *Ecology and Society* 17:1−15
30. Johansson M, Rooke T, Fetene M, Granstro A 2010. Browser selectivity alters post-fire competition between *Erica arborea* and *E . trimera* in the sub-alpine heathlands of Ethiopia. *Plant Ecology* 149−160. https://doi.org/10.1007/s11258-009-9661-9
31. Adeyemo SM, Granger JJ. 2023. Habitat suitability model and range shift analysis for American Chestnut (*Castanea dentata*) in the United States. *Trees, Forests and People* 11:100360
32. Haile M, Semere H, Birhane E, Abraha Z, Rannestad MM, et al. 2023. Distribution of expansive shrubs under climate change scenarios and their socio-economic impacts in a dry Afromontane Forest. *Trees, Forests and People* 13:1−15
33. Fandos G, Feng X, Guillera-arroita G, Guisan A, Lahoz-monfort JJ, et al. 2020. A standard protocol for reporting species distribution models. *Ecography* 43:1−17
34. Robiansyah I, Hajar S, Hajar AS. 2015. Predicting Current and Future Distribution of Endangered Tree *Dracaena ombet* Kotschy and Peyr. Under Climate Change. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences 1−10
35. Phillips SJ, Avenue P, Park F 2004. A Maximum Entropy Approach to Species Distribution Modeling. 655−662
36. Birhane E, Desalegn T, Kebede F, Giday K, Hishe H, et al. 2019. In situ leaf litter production, decomposition and nutrient release of

dry Afromontane trees. *East African Agricultural and Forestry Journal* 0:1–15
37. Aynekulu E, Aerts R, Denich M, Boehmer HJ 2016. Plant diversity and regeneration in a disturbed isolated dry Afromontane forest in northern Ethiopia. *Folia Geobotanica*. https://doi.org/10.1007/s12224-016-9247-y
38. WeForest and GIZ. 2019. Exploratory Forest Resources Survey in Tigray. Mekelle
39. Wanga VO, Ngarega BK, Oulo MA, Mkala EM, Ngumbau VM, et al. 2024. Projected impacts of climate change on the habitat of Xerophyta species in Africa. *Plant Diversity* 46:91−100
40. Kurpis J, Serrato-cruz MA, Patricia T, Arroyo F. 2019. Modeling the effects of climate change on the distribution of *Tagetes lucida* Cav. (Asteraceae). *Global Ecology and Conservation* 20:1−11
41. Gebrewahid Y, Abrehe S, Meresa E, Eyasu G, Abay K, et al. 2020. Current and future predicting potential areas of *Oxytenanthera abyssinica* (A. Richard) using MaxEnt model under climate change in Northern Ethiopia. *Ecological Processes* 9
42. Hijmans R, Cameron S, Parra J, Jones P, Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965−1978
43. Jacobsen CD, Brown DJ, Flint WD, Pauley TK, Buhlmann KA, et al. 2020. Vulnerability of high-elevation endemic salamanders to climate change: A case study with the Cow Knob Salamander (*Plethodon punctatus*). *Global Ecology and Conservation* 21:e00883
44. Phillips SJ, Anderson RP, Schapire RE. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190:231−259
45. Phillips SJ, Anderson RP, Dudík M, Schapire RE, Blair ME, et al. 2017. Opening the black box: an open-source release of Maxent. *Ecography* 40:887−893
46. Moscetti R, Hagos D, Agrimi M, Haff RP, Liang P, et al. 2021. Pine nut species recognition using NIR spectroscopy and image analysis. *Journal of Food Engineering* 292:110357
47. He Q, Zhao R, Zhu Z. 2020. Geographical distribution simulation and comparative analysis of *Carpinus viminea* and *C. londoniana*. *Global Ecology and Conservation* 21:e00825
48. Dai X, Wu W, Ji L, Tian S, Yang B, et al. 2022. MaxEnt model-based prediction of potential distributions of *Parnassia wightiana* (Celastraceae) in China. *Biodiversity and Conservation* 10:1−16
49. Mir AH, Tyub S, Kamili AN 2020 Ecology, distribution mapping and conservation implications of four critically endangered endemic plants of Kashmir Himalaya. *Saudi Journal of Biological Sciences* 27: 2380–2389. https://doi.org/10.1016/j.sjbs.2020.05.006
50. IUCN Standards and Petitions Committee 2019. Guidelines for Using the IUCN Red List Categories and Criteria
51. Kumar S, Stohlgren TJ 2009. Maxent modeling for predicting suitable habitat for threatened and endangered tree *Canacomyrica monticola* in New Caledonia. *Journal of Ecology and Natural Environment* 1: 094–096
52. Yan H, Feng LL, Zhao Y, Feng LL, Zhu C. 2020. Predicting the potential distribution of an invasive species, *Erigeron canadensis* L., in China with a maximum entropy model. *Global Ecology and Conservation* 21:e00822
53. Birhane E, Gidey T, Abrha H, Brhan A, Zenebe A, et al. 2023. Impact of land-use and climate change on the population structure and distribution range of the rare and endangered *Dracaena ombet* and *Dobera glabra* in northern Ethiopia. *Journal for Nature Conservation* 76
54. Gufi Y, Manaye A, Tesfamariam B, Abrha H. 2023. Modeling impacts of climate change on the geographic distribution and abundances of *Tamarindus indica* in Tigray region, Ethiopia. *Heliyon* 9:e17471
55. Gufi Y, Manaye A, Tesfamariam B, Abrha H. , Gidey T, et al. 2023. Modeling climate change impact on distribution and abundance of *Balanites aegyptiaca* in drylands of Ethiopia. *Modeling Earth Systems and Environment* 1–13
56. Fernando L, Cherenet E. 2023. Climate changes could jeopardize a main source of livelihood in Africa's drylands. *Journal for Nature Conservation* 71:126319
57. Moudrý V, Bazzichetto M, Remelgado R, Devillers R, Lenoir J, et al. 2024. Optimising occurrence data in species distribution models: sample size, positional uncertainty, and sampling bias matter. *Ecography* 1–20. https://doi.org/10.1111/ecog.07294
58. Mkala EM, Mutinda ES, Wanga VO, Oulo MA, Oluoch WA, et al. 2022. Modeling impacts of climate change on the potential distribution of three endemic Aloe species critically endangered in East Africa. *Ecological Informatics* 71:101765
59. Pinedo-alvarez C, Renteria-villalobos M, Aguilar-soto V, Vega-mares JH, Melgoza-castillo A. 2019. Distribution dynamics of *Picea chihuahuana* Martínez populations under different climate change scenarios in Mexico. *Global Ecology and Conservation* 17:e00559
60. Wang J, Wang F, Wang R, Zhang J, Zhao X, et al. 2019. Modeling the effects of bioclimatic characteristics and distribution on the occurrence of *Cyrtotrachelus buqueti* in the Sichuan Basin. *Global Ecology and Conservation* 17:e00540
61. Khafagia O, Omarb K 2018. Geographical attributes analysis for Egyptian *Hypericum sinaicum*. Universal Journal of Environmental Research and Technology 500–514
62. Tefera AS, Ayoade JO, Bello NJ. 2019. Comparative analyses of SPI and SPEI as drought assessment tools in Tigray Region, Northern Ethiopia. *SN Applied Sciences* 1:1−15
63. Yimer F, Ledin S, Abdelkadir A. 2006. Soil organic carbon and total nitrogen stocks as affected by topographic aspect and vegetation in the Bale Mountains, Ethiopia. *Geo* 135:335−344
64. Aerts R 2019. Forest and Woodland Vegetation in the Highlands of Dogu'a Tembien. In: Nyssen J, Jacob M, Frankl A (eds) Geo-trekking in Ethiopia's Tropical Mountains: The Dogu'a Tembien District. pp 233–250
65. Gidey T, Birhane E, Solomon N, Atsbha T, Hn J, et al. 2024. Population and conservation status of the endangered *Dracaena ombet* tree in dry Afromontane forests. *Global Ecology and Conservation* 50:1−11