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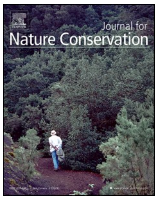

Impact of land-use and climate change on the population structure and distribution range of the rare and endangered *Dracaena ombet* and *Dobera glabra* in northern Ethiopia

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ABSTRACT

Dracaena ombet and *Dobera glabra* are some of the most important rare and endangered tree species in dryland areas. Unfortunately, their sustainability is being compromised by different anthropogenic and natural factors. However, impacts of the on-going land-use and climate change on the population structure and distribution of the species are less explored. This study was carried out in the grazing lands and hillside areas of the Desa'a dry Afromontane-forest, northern Ethiopia, to characterize the population structure of the species and predict the impact of climate change on their potential distributions. In each land-use type, abundance, diameter and height of the trees were collected using 70 sampling plots distributed over seven transects spaced one km apart. The geographic coordinates of each individual tree were also recorded. The results showed that the species populations were characterized by low abundance and unstable population structure. The latter was evinced by a lack of seedlings and mature trees. The study also revealed that the total abundance and dendrometric traits of the trees were significantly different between the two land-uses. The hillside areas had denser abundance with bigger and taller trees than the grazing lands. Climate change predictions using the MaxEnt model highlighted that future temperature increases coupled with reduced precipitation would lead to significant reductions in the suitable habitats of the species in northern Ethiopia. The species suitable habitats were predicted to decline by 48–83% for *D. ombet* and 35–87% for *D. glabra*. Hence, to sustain the species populations, different strategies should be adopted, namely the introduction of alternative livelihoods (e.g., gathering NTFP) to reduce the overexploitation of the species for subsistence livelihood, and the protection of the current habitats of the species that will remain suitable in the future using community-based exclosures. Additionally, the preservation of the species' seeds in gene banks is crucial to ensure their long-term conservation.

1. Introduction

Climate change is forecasted to raise global temperature by 4.3 ± 0.7 in the end of 2100, with low or heavy precipitation events becoming more frequent (Pachauri et al., 2014). Such changes are expected to have a substantial impact on plant growth (Nord and Lynch, 2009; IPCC, 2014). Climate change is also anticipated to strongly influence dryland Rare and Endangered Tree Species (RETs) as these trees have evolved narrow climatic tolerances due to their little intra-annual variability in temperature (Blach-Overgaard et al., 2010; Vale and Brito, 2015). On the one hand, climate change is expected to alter the phenological and physiological characteristics of RETs (Stévart et al., 2019). On the other hand, changes in climatic conditions would cause a shift in the latitudinal and elevation ranges of RETs, thereby either contracting or fragmenting their natural habitats (Dotchamou et al., 2016; Noulekoun et al., 2017; Birhane et al., 2020). Under the scenario where species

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cannot migrate due to the lack of suitable habitats at higher elevations (You et al., 2018) or because they have evolved narrow climatic tolerances as a consequence of little intra-annual variation in temperature (Colwell et al., 2008; Blach-Overgaard et al., 2010), climate change is expected to lead to species extinction (Birhane et al., 2020; Dimobe et al., 2022; Biaou et al., 2023). The latter phenomenon is termed the ''the nowhere to go'' hypothesis (Nogués-Bravo et al., 2007; Loarie et al., 2009). The shift in species distribution range or species extinction may be followed by changes in ecological interactions of the RETs with other trophic levels including for instance insect pollinators and herbivores (Cornelissen, 2011; Travis et al., 2013). Consequently, climate change impacts would lead to the decline in the RETs diversity and the diverse ecosystem functions and services that they provide (Dotchamou et al., 2016; Birhane et al., 2020; Dimobe et al., 2022; Gufi et al., 2023).

Species distribution models (SDMs) have been extensively used to predict the current and future potential distributions of species (Booth et al., 2014; Birhane et al., 2020; Biaou et al., 2023). SDMs predict the spatial distribution of species based on occurrence records and digital layers of environmental data (Elith et al., 2011; Zhang et al., 2019). SDMs allow the prediction of the impact of future climate on species distribution when fetched with future climate scenarios. Among the many available SDMs models, the Maximum Entropy (MaxEnt) algorithm has been widely used because of its superior performance (Phillips et al., 2006). MaxEnt requires low sample size and provides accurate and reliable predictions even under small sample sizes. It also ranks the importance of individual environmental variables for a species distribution (Hernandez et al., 2006; Elith et al., 2011). MaxEnt mainly combines presence-only occurrence records with environmental data to algorithmically estimate species' distributions, and then project the species niches onto the landscape, reflecting species' habitat preferences in the form of a probability (Elith and Leathwick, 2009). The model has already been employed to predict the impacts of climate, land use and other environmental changes on the distribution of RETs in dryland areas (Vieilledent et al., 2013; Robiansyah and Hajar, 2015; Noulekoun et al., 2017; Birhane et al., 2020; Dimobe et al., 2022; Gufi et al., 2023).

Dracaena ombet Kotschy and Peyr. is an evergreen tree that grows to about 5–8 m height, with a densely packed crown (Kotschy, 1867). Its trunk is forked and divided into several branches, with sword-shaped leaves. The leaves are thick and erect in position to reduce transpiration (Kotschy, 1867). It has white flowers and has spherical berries each containing one to three small seeds (Bauerová et al., 2020). The seeds have a long dormancy and are dispersed by birds, water, and wind (Ghazali et al., 2008). *D. ombet* populations are found in Egypt, Sudan, Ethiopia, Eritrea, Somalia, Djibouti and Saudi Arabia (Ghazali et al., 2008; Aynekulu, 2011), at elevations ranging between 1000 and 1800 m.a.s.l with an annual rainfall of 200–500 mm (Kamel et al., 2014). However, Andersen et al. (Andersen et al., 2022) reported a shift of *D. ombet* populations towards higher elevations, possibly due to climate change in Red Sea Hills, Sudan. *Dobera glabra* (Forssk.) Poir. is a much-branched evergreen tree and its height reaches 7–12 m (Befkadu et al., 2021). It has an alternate thick, skinny leaves. Its flowers are white and have ovoid fruits, each containing one to two seeds (Tsegaye et al., 2007). *D. glabra* is distributed in India, Kenya, Saudi Arabia, Sudan, Tanzania, Ethiopia, Djibouti, Uganda and Yemen (Vogt, 1995), at elevations ranging between 400 and 1250 m.a.s.l (Tsegaye et al., 2007).

D. ombet and *D. glabra* are two of the most important dryland RETs in the Horn of Africa (Andersen et al., 2022; Gebrehiwot and Zeynu, 2022). The species provide substantial socio-economic, cultural, and ecologic values in dryland areas (Tsegaye et al., 2007, Tsegaye et al., 2010; (WeForest., 2018). For instance, in Ethiopia, *D. ombet* is a source of livelihood for the local people through the harvest of its plant parts for making farm equipment and household utensils (Gidey et al., 2023). *D. glabra* is harvested for its fruits, which are commonly used for human food during dry seasons (Tsegaye et al., 2007). Besides, both trees are used to forecast drought episodes by observing their morphological changes (Tsegaye et al., 2007, (Gidey et al., 2023). They are also valued for livestock feed, medicine, soil and water conservation, and adaptation to climate change impacts (WeForest., 2018; Gebrehiwot and Zeynu, 2022). Despite the wide benefits that the trees provide to humans, they are now heavily threatened by land-use change, overexploitation, and habitat degradation (Tsegaye et al., 2010; WeForest., 2018; Gebrehiwot and Zeynu, 2022). These adverse effects on the species populations have recently been intensified by climate change (WeForest., 2018; Gebrehiwot and Zeynu, 2022; Andersen et al., 2022). This has led the populations to become more scattered with small and isolated patches with unbalanced age structures (Lengálová et al., 2020; Gebrehiwot and Zeynu, 2022). As a result, *D. ombet* has been listed on the International Union for Conservation of Nature (IUCN) Red List as globally endangered tree species (Iucn, 2017). Both trees have also been identified as highly RETs in Ethiopia (Tsegaye et al., 2010; WeForest., 2018). Therefore, assessing the impacts of land-use and climate change on the population structure and distribution range of *D. ombet* and *D. glabra* species is crucial to devise effective conservation and management strategies.

In this study, various data on the structure (e.g., diameter at stump and breast heights) and geographic location (e.g., geographic coordinates) of the species populations were collected in two major land-use types (grazing lands and hillside areas) from the Tigray and Afar regions of northern Ethiopia, where there is little information to date regarding the impacts of the on-going land-use and climate change on the population structure and distributions of the species (WeForest., 2018). The study aims to 1) characterize the abundance and population structure of *D. ombet* and *D. glabra* under the two land-use types; 2) identify the main environmental variables affecting the potential suitable habitats of the species; and 3) estimate the impact of future climate change on the distribution of the species in northern Ethiopia. We hypothesized that 1) the abundance and structural characteristics of the species populations will be lower in the grazing lands than hillside areas due to higher level of human disturbances in the grazing lands, and 2) projected increase in temperature and decrease in precipitation will reduce the distribution range of the species due to limitation of range expansion in line with the prediction of ''the nowhere to go'' hypothesis.

2. Methods

2.1. Study area

The field data were collected from the Desa'a dry Afromontane forest (13° 20′–14° 10′N; 39° 32′–39° 55′E), which is located in northern Ethiopia (Fig. 1). The forest covers about 154,000 ha (WeForest., 2018). The forest provides high economic, ecologic and cultural values to the nearby local people (Aynekulu, 2011; WeForest., 2018). It is a source of income and other several ecological services for nearly a half million people (WeForest., 2018). The forest is also selected as one of the biodiversity hubs for the implementation of the international climate change mitigation programme, called the REDD$^+$ program (Tetemke et al., 2019).

Desa'a forest is characterized by large elevation gradients, ranging from 3100 m.a.s.l in the highlands of Tigray to 900 m.a.s.l in the lowlands of Afar (WeForest., 2018). The average annual temperature and precipitation range between 13 and 25 °C and 400 to 700 mm, respectively (Hishe et al., 2021). The dominant soil types are Leptosols, Cambisols, Vertisols, Regosols and Arenosols (BoANR., 1997). The slopes are gentle to steep, and frequently dissected by stream incisions. The variability in climate, elevation and soil makes the forest home to a wide diversity of flora and fauna species, of which several are RETs (Aynekulu, 2011). Within the forest, *D. ombet* occurs with *Vachellia etbaica* (Schweinf.) Kyal. & Boatwr. communities at elevations between 1000 and 2000 m.a.s.l, and *D. glabra* co-exists with *Senegalia mellifera* (Vahl) Seigler & Ebinger communities at elevations ranging between 600 and 1800 m.a.s.l (Aynekulu, 2011); Personal observation). The area includes various land-use types such as rangelands (grazing lands),

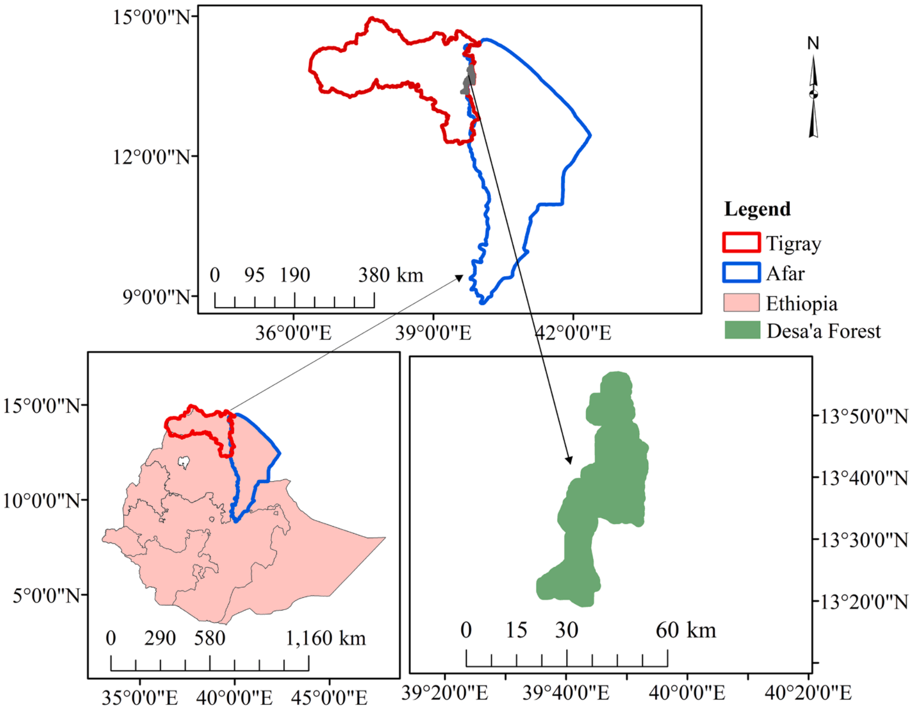

Fig. 1. Geographic location of the Desa'a forest and the Tigray and Afar regions in Ethiopia.

hillside areas, forests, valleys, farmlands, and barren lands. *D. ombet* and *D. glabra* are mainly found in the grazing and hillside areas (Aynekulu, 2011).

2.2. Sampling techniques and data collection

Based on the occurrence of the species (Aynekulu, 2011; WeForest., 2018), two land-use types (grazing lands and hillside areas) within the Desa'a forest were selected for the study. The comprehensive land-use map of the Desa'a forest (WeForest., 2018) and a reconnaissance survey were used to locate the land-uses. Next, inventory was conducted from April to August 2020 in each land-use using a systematic transect sampling technique. In each land-use type, seven parallel transects of 500 m long and 20 m wide (1 ha) set one km apart were established along the elevation gradient in the east–west direction. Each transect line was then divided into 10 plots of 20 m × 20 m set 50 m apart. The first sampling plot was laid entering 50 m from the edge of the land-use. A total of 70 plots were established in each land-use. In each plot, the abundance of the trees was counted, and the diameter at breast height (1.3 m above the ground level – dbh) was measured. Additionally, the diameter at stump height (0.1 m above the ground level – dsh) was measured for plants that had a height < 1.3 m (Köhl, 1993). The dbh and dsh were measured using a diameter tape and a calliper, respectively. The height of the species was measured using a bamboo stick of 5 m height, graduated with 10 cm markings. Besides, the geographic coordinates of each individual tree of the species found in the sample plots were recorded as decimal latitude/longitude using a hand-held Garmin 74 GPS. The occurrence data of the species in Tigray and Afar regions of northern Ethiopia (outside the study forest) were also retrieved from the Global Biodiversity Information Facility (www.gbif.org, accessed on 02, April 2023). Accordingly, a total of 430 and 200 occurrence records were used for the analysis of the potential distribution of *D. ombet and D. glabra* populations, respectively, using the MaxEnt model.

2.3. Statistical data analysis

To analyse the abundance of the trees in each land-use type, the recorded *D. ombet* trees were classified into three ontogenetic stages based on findings from previous studies on the species that covered ecological conditions similar to the ones prevailing in our study area and opinions of the local people (Ghazali et al., 2008; Andersen et al., 2022; Personal communication). Accordingly, *D. ombet* trees were divided into seedlings (dsh < 2 cm and height < 0.5 m) saplings (dsh $= 2$–8 cm and height $= 0.5$–1.3 m or dbh $= 2$–8 cm and height $= 1.3$–1.6 m) and mature trees (dbh > 8 cm and height > 1.6 m). *D. glabra* trees were also classified into seedlings (dsh < 3 cm and height < 0.5 m), saplings (dsh $= 3$–8 cm and height $= 0.5$–1.3 m or dbh $= 3$–8 cm and height $= 1.3$–1.6 m) and mature trees (dbh > 8 cm and height > 1.6 m) (Tsegaye et al., 2010; Gebrehiwot and Zeynu, 2022; Personal communication). The species population structures were further characterized graphically using the size-class distributions (SCDs). The differences in the abundance (e.g., the total abundance, the abundance of seedlings, saplings, and mature trees) and dendrometric parameters (e.g., dsh, dbh and height) between the land-uses were assessed using the Kruskal-Wallis nonparametric test as the data did not meet the assumption of normality. The Statistical Analysis Software (SAS) version 9.2 was used for the data analysis.

2.4. Environmental datasets

The recorded occurrence data of the species were inserted into MaxEnt along with the environmental data to predict their current and future potential distributions in Tigray and Afar regions, northern Ethiopia. The environmental dataset comprised of the 19 bioclimatic variables (Hijmans et al., 2005) and three non-climatic variables: elevation, slope, and soil types (Appendix, Table A1). The current (1950–2000) and future (2050, 2070) bioclimatic and elevation data were downloaded from the WorldClim database (http://www.worldclim.org, accessed on 12, April 2023) and clipped down to the extension of the map of the study regions in Arc GIS 10.1. Slope data were derived from the Digital Elevation Model using surface analysis extension in Arc GIS 10.1. The soil types were extracted from the FAO/UNESCO Soil Map of the World (https://www.fao.org/soils-portal/en/, accessed on 15, April 2023). All the 22 layers were used at a resolution of 1 km.

To predict the future distribution of the species, projected climate data for 2050 (average for 2041–2060) and 2070 (2061–2080) based on the Representative Concentration Pathways (RCP) 4.5 and 8.5 emission scenarios were used. The RCP 4.5 and 8.5 represent climate conditions under which the radiative forcing is projected to increase by 4.5 and 8.5 W m^{-2} by the year 2100, respectively. This would be equivalent to an increase of 2.4 or 4.9 °C by 2100 in the world (Wayne, 2013). The future climate data were obtained from three general circulation models (GCM): CCSM4, ACCESS1-0 and MIROC5. These GCMs were used as they had produced reasonable results in Ethiopia (Noulekoun et al., 2017; Birhane et al., 2020; Gufi et al., 2023). The average output of the three models was used for the prediction of the future distribution of the species to reduce model uncertainty due to inherent structural dissimilarities among the GCMs.

2.5. *Model performance, suitability maps and contribution of environmental variables*

The ability of MaxEnt to predict the observed spatial distribution of the species was assessed by splitting the recorded occurrence data into random training (75 %) and test (25 %) datasets and by randomly selecting 5,000 pseudo-absence points from the whole study regions, which were associated to the presence data to form the presence-absence datasets (Phillips and Dudik, 2008). To improve model accuracy and minimize the level of uncertainty, 15-fold cross-validation was used in which the model was run 15 times and the results were then averaged (Robiansyah and Hajar, 2015). As multicollinearity may influence the accuracy of the model predictions, highly correlated environmental variables were discarded. For this, the Pearson correlation coefficient (r) between each pair of bioclimatic variables was determined (Warren et al., 2010), and $r = 0.8$ was considered as a cut-off threshold for the exclusion of highly correlated variables, i.e., $r > 0.8$ (Robiansyah and Hajar, 2015). For example, precipitation seasonality and precipitation of driest quarter ($r = 0.89$), as well as temperature annual range and precipitation of wettest quarter ($r = 0.91$) were highly correlated variables, and thus excluded from the analyses performed for *D. ombet* and *D. glabra*, respectively. The predictive performance of the model was measured using the area under the curve (AUC), derived from the receiver operating characteristic (ROC). AUC is an effective threshold-independent measure of the model performance (Thuiller et al., 2005) and its value ranges between 0.5 and 1. The model accuracy can be described based on the following AUC classes: AUC $\geq$ 0.90 (excellent), AUC = 0.8–0.9 (good), AUC = 0.7–0.80 (acceptable), AUC = 0.6–0.70 (bad), and AUC = 0.5–0.60 (invalid) (Thuiller et al., 2008).

The model output is a continuous raster of probability values ranging between 0 and 1, which represents the suitable habitats (Phillips et al., 2006). Accordingly, suitable areas for the species occurrence were produced using the ten-percentile training threshold (0.43) generated by the model. Hence, the set of grid cells for which the absence-presence prediction was greater than 0.43 represented the present suitable habitats in the study regions (Vieilledent et al., 2013). Future suitable habitats for the species were also identified by overlaying and reclassifying the binary rasters of current and future potential distributions, thereby defining four levels of suitability ranging from unsuitable (high-impact areas) to highly suitable (new suitable areas) (Scheldeman and Zonneveld, 2010). The results were visualized in DIVA-GIS 7.5.

Furthermore, the percent contribution and the internal jackknife test were used to evaluate the importance of each environmental variable in predicting the current distribution of the species (Phillips and Dudik, 2008; Noulekoun et al., 2017; Birhane et al., 2020; Biaou et al., 2023; Gufi et al., 2023). Important variables included those with high percent contribution and high decrease in gain when removed from the model (Phillips et al., 2006).

3. Results

3.1. *Population structure*

The total abundance of *D. ombet* in the two land-use types was 157 ± 7.4 stems ha^{1}, with a comparatively high number of mature trees than saplings (Table 1). Both abundance and dendrometric traits (dsh, dbh and height) of the species were significantly different between the land-uses. Accordingly, the total abundance was significantly higher in the hillside areas than the grazing lands. Similarly, the biggest and tallest trees recorded in the hillside areas (Table 1). The SCDs for the whole *D. ombet* populations in the two land-uses highlighted that the species lacked regeneration, i.e., seedlings and saplings (e.g., dbh between 2 and 5 cm). Besides, most of the individual trees were found in the 5–25 cm dbh size-classes. The upper SCDs were characterized by lack of old trees (dbh $>$ 25 cm) (Fig. 2).

In the two land-use types, the total abundance of *D. glabra* was 39 ± 7.5 stems ha^{-1}, with a relatively higher number of mature trees than saplings (Table 1). When compared between the land-uses, the hillside areas had significantly higher number of mature trees, the biggest and tallest trees than the grazing lands (Table 1). The whole *D. glabra* populations were characterized by the lack of regeneration, i.e., seedlings (dsh $<$ 3 cm) and saplings (e.g., dbh between 3 and 5 cm). Furthermore, the upper SCDs showed lack of trees with dbh $>$ 20 cm (i.e., old trees). There were more trees in the 5.1–10 cm, 20.1–25 cm and 25.1–30 cm size classes than in the 10.1–15 cm and 15.1–20 cm size classes (Fig. 2).

3.2. *MaxEnt performance and contribution of environmental variables*

The AUC values for *D. ombet* and *D. glabra* were 0.99 and 0.97, respectively, which were higher than the values that would be expected at random (Appendix, Fig. A1). These were good evidence that the MaxEnt model can be used for predicting the potential distributions of the species in the study regions.

Based on the percent contribution and the outputs of the internal jackknife test, the most important environmental variables associated with the distribution of *D. ombet* in the study regions were more related to precipitation such as precipitation of the warmest quarter and annual precipitation. To some extent, temperature related variables like maximum temperature of warmest month were found as a significant factor explaining the distribution of the species (Table 2; Appendix, Fig. A2). However, precipitation related variables together contributed for more than 70 % to the distribution of the species while temperature related variables contributed for 20 % only (Appendix, Table A2).

Similarly, the potential distribution of *D. glabra* in the study regions was more linked to precipitation variables such precipitation of driest month and warmest quarter than temperature related factors like maximum temperature of warmest month (Table 2; Appendix, Fig. A2). Overall, precipitation related variables contributed for about 75 % in explaining the distribution of the species whereas temperature related factors had a contribution of nearly 25 % only (Appendix, Table A3).

3.3. *Current and future distributions of the species*

In terms of the current potential distribution, *D. ombet* is mainly found in the low- and midland areas of eastern Tigray and western Afar covering 4.2 % of the study regions (Fig. 3A). However, its future predictions indicated a great reduction of suitable habitats across the future climatic scenarios (Fig. 3B–E). The 4.2 % coverage of the species under current climate is expected to decrease by 3 %, 3 %, 2 % and 3.5 % in 2050-RCP 4.5, 2050-RCP 8.5, 2070-RCP 4.5, and 2070-RCP 8.5, respectively (Fig. 3A–E). The predicted reductions in suitable habitats of the species were mainly associated with a decrease in the annual precipitation (60–90 mm in RCP 4.5 and 50–100 mm in RCP 8.5) and an increase in the maximum temperature of the warmest month (0.6–3.0 °C in RCP 4.5 and 1.1–4.0 °C in RCP 8.5) in the study regions (Table 3).

Table 1
Abundance (stem ha^{-1}), dsh and dbh (cm), and height (m) of *D. ombet* and *D. glabra* in the two land-use types in the Desa'a dry Afromontane forest, northern Ethiopia.

Parameters	Tree species	Grazing lands Mean (±SEM)	Hillside areas Mean (±SEM)	Whole population Mean (±SEM)
Total abundance	*D. ombet*	128^b (±6.6)	185^a (±8.2)	157 (±7.4)
	D. glabra	34^b (±6.3)	44^a (±8.8)	39 (±7.5)
Saplings	*D. ombet*	33^b (±8.4)	42^a (±12.3)	38 (±10.3)
	D. glabra	9^b (±4.7)	14^a (±5.2)	11 (±5.0)
Mature trees	*D. ombet*	95^b (±9.6)	143^a (±11.4)	119 (±10.5)
dsh	*D. glabra*	25^b (±7.5)	30^a (±8.5)	28 (±8.0)
	D. ombet	1.2^b (±1.2)	1.5^a (±1.4)	1.3 (±1.3)
	D. glabra	1.7^b (±1.3)	2.1^a (±1.5)	1.9 (±1.4)
dbh	*D. ombet*	20.1^b (±2.0)	21.1^a (±3.2)	20.6 (±2.6)
	D. glabra	21.5^b (±2.0)	23.7^a (±2.4)	22.6 (±2.2)
Height	*D. ombet*	3.2^b (±0.6)	3.9^a (±0.8)	3.6 (±0.7)
	D. glabra	4.7^b (±0.7)	5.9^a (±0.9)	5.3 (±0.8)

Data on seedlings are not presented because there were no seedlings. Within the same rows, the means with the same letters are not significantly different at $p < 0.05$. dsh = diameter at stump height, dbh = diameter at breast height, SEM = standard error of the mean.

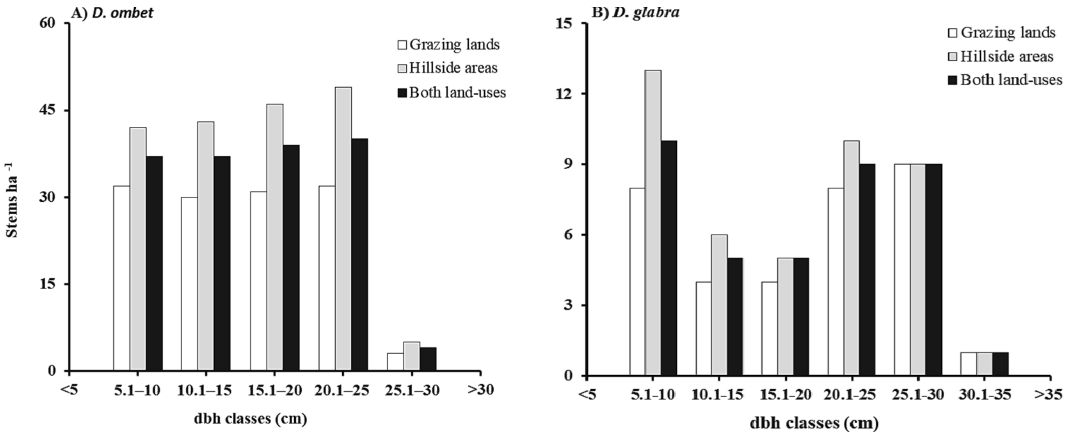

Fig. 2. dbh size-class distributions of *D. ombet* and *D. glabra* in the two land-use types in the Desa'a dry Afromontane forest, northern Ethiopia.

Table 2
Relative contribution of the top-five environmental variables in the MaxEnt model to predict distributions of D. ombet (details found in the Appendix, Table A2) and D. glabra (details found in the Appendix, Table A3).

D. ombet			*D. glabra*		
Variables	Description	% contribution	Variables	Description	% contribution
bio18	Precipitation of warmest quarter	31.8	bio14	Precipitation of driest month	30.5
bio12	Annual precipitation	25.2	bio18	Precipitation of warmest quarter	22.8
bio5	Max temperature of warmest month	18.5	bio12	Annual precipitation	21.5
bio14	Precipitation of driest month	9.8	bio5	Max temperature of warmest month	9.1
bio19	Precipitation of coldest quarter	6.0	bio19	Precipitation of coldest quarter	5.2

However, the future predictions did not indicate a shift of the species populations towards higher elevations, as evidenced by the similar elevation range observed for both the current and future distributions of the species (Table 3).

In the study regions, *D. glabra* populations had an area coverage of 8.6 % under the current climate, mainly distributed in the low- and midland areas of eastern Tigray and western Afar (Fig. 4A). The future climatic scenarios predicted a substantial reduction in the suitable habitats of the species, with no upward shift of the species populations. However, we observed a shift towards lower elevations under 2070-RCP 4.5 and 2070-RCP 8.5 (Table 3; Fig. 4B–E). The current 8.6 % coverage of the species will be reduced by 5 %, 6.5 %, 3 % and 7.5 % under 2050-RCP 4.5, 2050-RCP 8.5, 2070-RCP 4.5, and 2070-RCP 8.5, respectively (Fig. 4A–E). The predicted changes in the suitable habitats of the species were mainly due to the decrease of annual precipitation (23–43 mm in RCP 4.5 and 21– 94 mm in RCP 8.5) and an increase in the maximum temperature of the warmest month (1.7–2.9 °C in RCP 4.5 and 1.1–4.0 °C in RCP 8.5) (Table 3).

4. Discussion

4.1. Population structure of the species

The study showed that both the rare and endangered *D. ombet* and *D. glabra* were characterized by low abundance and unstable population structure in the grazing and hillside areas of the Desa'a dry Afromontane

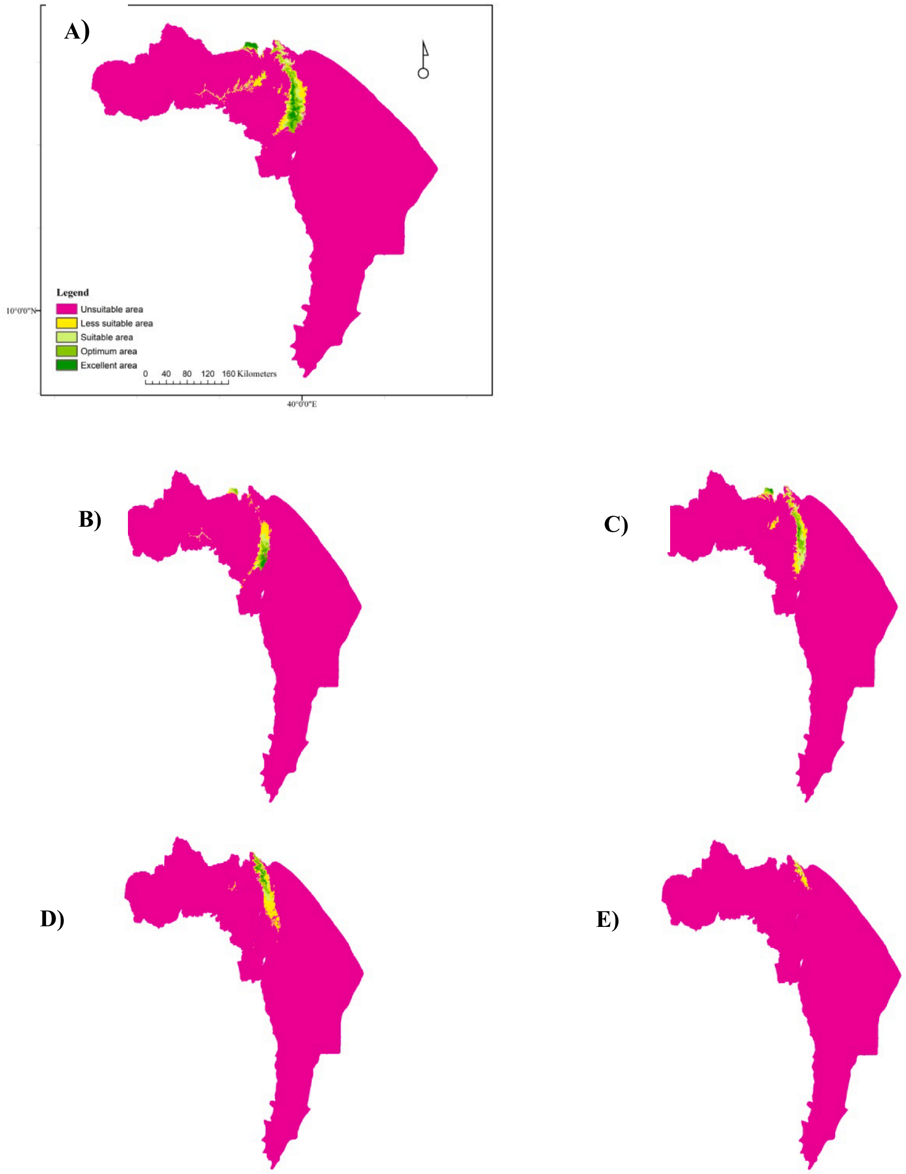

Fig. 3. Distribution maps of *D. ombet* indicating the suitable habitats under current (A) and future climate scenarios: 2050-RCP 4.5 (B), 2050-RCP 8.5 (C), 2070-RCP 4.5 (D), 2070-RCP 8.5 (E) in Tigray and Afar regions, northern Ethiopia. RCP = Representative Concentration Pathways.

Table 3
Environmental conditions across the suitable habitats of *D. ombet* and *D. glabra* under the current and future climate change scenarios in the study regions.

Climate scenarios	Tree species	Annual precipitation (mm)	Maximum temperature of warmest month (°C)	Elevation (m)
Current	*D. ombet*	300–400	24.0–41.2	600–2600
	D. glabra	303–398	25.8–41.5	338–2502
2050-RCP 4.5	*D. ombet*	270–360	24.6–42.3	614–2537
	D. glabra	300–390	26.1–41.9	474–2498
2050-RCP 8.5	*D. ombet*	250–330	25.1–41.9	316–2488
	D. glabra	282–385	26.8–42.2	331–2452
2070-RCP 4.5	*D. ombet*	240–310	25.7–44.2	701–2552
	D. glabra	260–375	27.1–43.1	164–2340
2070-RCP 8.5	*D. ombet*	230–300	27.9–45.2	460–2490
	D. glabra	250–304	28.3–44.1	181–2201

RCP = Representative Concentration Pathways.

forest. The unstable population structure was evidenced by the critical lack of regeneration, mainly seedlings, and mature trees. Similar structural problems were reported for the species elsewhere. For example, WeForest (WeForest., 2018) found that the remaining populations of *D. ombet* in northern Ethiopia had low abundance (113 stems ha^{-1}). Ghazali et al. (Ghazali et al., 2008) also found that *D. ombet* populations in northern Egypt were characterized by a moderately low abundance (353 stems ha^{-1}) and no recruitments. Vahalik et al. (Vahalik et al., 2020) reported different abundances of *Dracaena serrulata* Baker trees, a species belonging to the same genus as *D. ombet*, in three areas within the Dhofar Mountains of Oman, at different elevations. The Jabal Samhan area, characterized by relatively higher elevations (1075–1579 m) and moderate rainfall included 1835 trees whereas the Jabal al Qamar area characterized by lower elevations (659–1082 m) and rainfall had only 552 trees. In addition, the prevailing *D. glabra* populations in northern Ethiopia exhibited very low abundance (18 stems ha^{-1}) and small number of saplings (Gebrehiwot and Zeynu, 2022). The low abundance and unstable structure of the tree species in Desa'a forest and other areas mentioned above could be due to the overexploitation of the

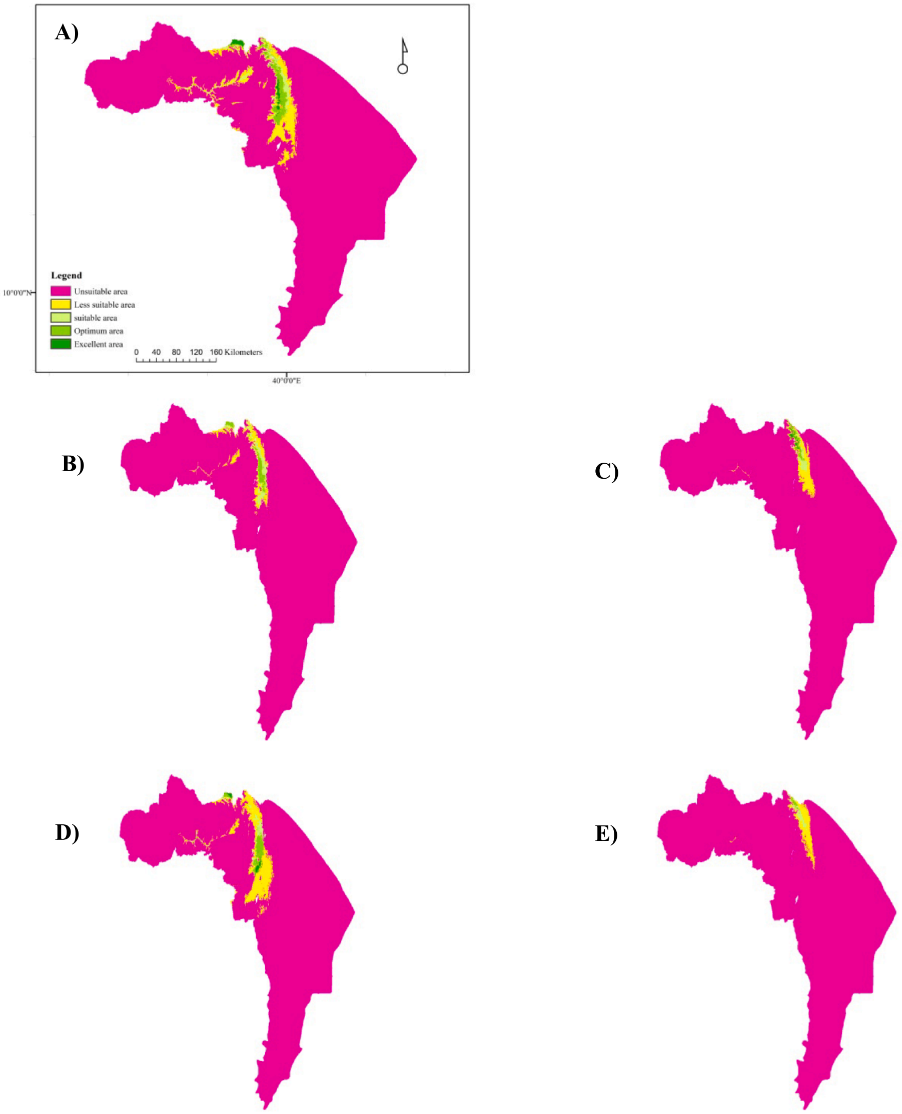

Fig. 4. Distribution maps of *D. glabra* indicating the suitable habitats under current (A) and future climate scenarios: 2050-RCP 4.5 (B), 2050-RCP 8.5 (C), 2070-RCP 4.5 (D), 2070-RCP 8.5 (E) in Tigray and Afar regions, northern Ethiopia. RCP = Representative Concentration Pathways.

species for local uses. For example, the local people intensively harvested *D. ombet* plant parts (e.g., stem, bark, and leaves) for preparing household utensils to be sold at local market (Gidey et al., 2023). They also overexploited *D. glabra* for its fruits, barks, and leaves for a wide range of purposes (Tsegaye et al., 2010; Gebrehiwot and Zeynu, 2022). Consequently, overexploitation of the species in combination with other pressures (e.g., drought, overgrazing) are believed to have been affecting the species in the Desa'a forest for a long time and caused the remaining populations to be dominated by unhealthy trees (Lengálová et al., 2020; Gebrehiwot and Zeynu, 2022) that are confined to stony and eroded areas (Tsegaye et al., 2007; Aynekulu, 2011). Our findings also pointed out a problem of tree recruitment from the stage of saplings (i.e., 5.1 cm $\leq$ dbh $\leq$ 10 cm) to mature trees (dbh $>$ 20 cm) for *D. glabra*, indicating the high human pressure on the saplings as well as their high sensitivity to environment stress.

The study also showed that the abundance and dendrometric characteristics of the species significantly different between the land-use types. We found that the total tree abundance, number of mature trees and saplings as well as key traits such as dsh, dbh and height were higher in the hillside areas, characterized by lower grazing pressure. This observation is in line with our first hypothesis. Our results support the general argument that human disturbances (e.g., overgrazing) are the major threats for maintaining the populations of RETs in dryland areas (Noulekoun et al., 2017; Birhane et al., 2020; Gidey et al., 2023). These findings are also in line with other previous studies conducted in Egypt, the Desa'a forest and elsewhere. For example, Ghazali et al. (Ghazali et al., 2008) reported that overgrazing severely threatened the seedlings of *D. ombet* in the rangeland areas of northern Egypt. Similarly, overgrazing was found to decline regeneration of the species by reducing the number of viable seeds on the soil surface in Desa'a forest (WeForest., 2018). Besides, the saplings of the two species were browsed and trampled by different grazers in the Desa'a forest. The local communities also over-defoliated the mature trees of the species for livestock feed, particularly during dry seasons (Tsegaye et al., 2010; Gebrehiwot and Zeynu, 2022; Gidey et al., 2023). These factors increase the vulnerability of the trees to drought and erosion conditions (WeForest., 2018; Gidey et al., 2023). Overgrazing was also identified as the major cause of the low regeneration and high mortality of seedlings for other dragon tree species (e.g., *Dracaena cinnabari* Balf.f. (Maděra et al., 2020) and *D. serrulata* (Vahalik et al., 2020)as well as for several RETs in drylands (Giday et al., 2018; Birhane et al., 2020; Hishe et al., 2021).

4.2. *Impacts of climate change on the distributions of the species*

In agreement with our second hypothesis, we found that there will be a substantial reduction in the suitable habitats of the species across the future climatic scenarios: 48–83 % for *D. ombet* and 35–87 % for *D. glabra*. These projections are consistent with the predicted decrease of *D. ombet* under the future climatic scenarios in the north-east African region (Robiansyah and Hajar, 2015). *D. cinnabari* is a flagship tree of Socotra Island, Yemen, which belongs to the same genus as *D. ombet*. *D. cinnabari* currently occupies only 5 % of the Island habitats. Due to climate change, *D. cinnabari* is expected to decrease by 45 % in 2080 because of the anticipated increase of drought episodes (Attorre et al., 2007). Climate change impacts are also anticipated to intensify habitat degradation of *D. cinnabari*, and make its distribution more scattered with small, fragmented and isolated populations (Maděra et al., 2020). Thus, the impact of climate change on the distribution of *D. ombet* and *D. glabra* in this study are reminiscent of the trends observed for *D. cinnabari*.

Over time, the current observed geographical range of the species will likely decline due to the expected decrease in the future annual precipitation and increase of maximum temperature of the warmest month, which were identified as the most important factors determining the distribution of the species in the study regions (Table 3). The projected warmer temperature coupled with expected water stress arising from reduced precipitation under future climatic scenarios would alter the current suitable habitats of the species into unsuitable areas in the future. Our finding is consistent with the previous studies on *D. ombet* (Robiansyah and Hajar, 2015; Andersen et al., 2022) and other RETs in dryland areas such as *Parkia biglobosa* (Jacq.) R.Br. ex G.Don (Dotchamou et al., 2016); *Adansonia digitata* L. (Birhane et al., 2020) and *Pterocarpus erinaceus* Poir. (Dimobe et al., 2022; Biaou et al., 2023).

Previous studies reported an upward range shift for tropical species in response to warming climates (Colwell et al., 2008). However, such an elevation shift was not observed in the distribution range of *D. ombet* and *D. glabra* under the climate change scenarios in this study. This finding suggests that there would not be sufficient suitable habitats at higher elevations to facilitate the migration of these species to other suitable areas under future climate conditions, in line with the predictions of ’’the nowhere to go’’ hypothesis (Loarie et al., 2009). Alternatively, the subtle latitudinal and temperature gradients within the study area would have constrained range expansion, resulting in the decline of the suitable habitats (Colwell et al., 2008; Blach-Overgaard et al., 2010). However, our results contrasts with that of Andersen et al. (2022) who reported a shift of the *D. ombet* populations toward higher elevations under climate change in the Red Sea Hills, Sudan. The discrepancy between the studies could be related to the relatively higher elevation ranges (e.g., 600–2600 m for *D. ombet* in our study and 500–1500 in the study of Andersen et al. (2022) covered by our study, which may have rendered any potential upward shift largely unnoticeable. Conversely, we observed a range shift towards lower elevations under 2070-RCP 4.5 and 2070-RCP 8.5 for *D. glabra*. It is likely that the future climatic conditions at lower elevations match the optimum climatic conditions for the species occurrence, thereby allowing the species to colonise these new areas within its distribution range.

4.3. *Conservation interventions for the species*

The study revealed that the trees lacked regeneration, seedlings and saplings for sustaining their populations in the Desa’a dry Afromontane forest. Urgent conservation interventions are then crucial. For instance, the overexploitation of the species for generating income should be reduced by introducing alternative livelihood sources. In the Desa’a forest, various environmentally friendly alternative livelihoods have been suggested, including the collection of non-timber forest products (e.g., medicinal plants and honey), poultry farming and home gardening (Tamba et al., 2021; Gidey et al., 2023). Overgrazing in the species habitats can also be reduced through introducing livestock exclosures. This is important to enhance the conservation of the species as it improves the microclimate of the area, increasing the abundance of viable seeds and protecting the emerged seedlings (Ghazali et al., 2008; Tamba et al., 2021; Gidey et al., 2023).

Moreover, the expected rising temperature coupled with the precipitation stress would pose a serious threat to the survival of the species in the study regions under climate change. Therefore, in order to sustain the species in the near future, the current suitable habitats should be protected using different in-situ conservation interventions such as exclosures to support the growth of the existing stands (Ghazali et al., 2008; WeForest, 2018; Gidey et al., 2023). Planting seedlings of the species in their natural habitats as well as in new habitats predicted to be suitable for the occurrence of the species in the future, followed by full tending management should also be introduced (WeForest., 2018). Under the high emission scenario (e.g., 2070-RCP 8.5) where high range contraction is predicted for the species, priority may be provided to ex-situ conservation in forms of germplasm collections and gene banks to ensure the long-term conservation of the species (WeForest., 2018).

5. Conclusions

The study showed that the prevailing populations of the rare and endangered *D. ombet* and *D. glabra* in northern Ethiopia are characterized by low abundance and unstable population structure. The abundance and dendrometric traits of the species significantly differed between the grazing lands and hillside areas. The hillside land-use type had denser abundance with bigger and taller trees than the former. This implied that human disturbances (e.g., overgrazing) could be one of the major factors impacting the regeneration and the overall growth of the species. Despite the wide drought tolerances of the trees in dryland areas, the projected increase in future temperature and decrease in precipitation are likely to reduce their potential distribution ranges in northern Ethiopia. Hence, to ensure the sustainability of the species in northern Ethiopia, different conservation strategies should be developed, namely the introduction of alternative livelihoods (e.g., gathering non-timber forest products) to reduce the overexploitation of the trees for income generation. The current suitable habitats of the species should also be protected using community-based exclosures. Additionally, preservation seeds of the species in gene banks are essential to support their long-term conservation efforts.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jnc.2023.126506.

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