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Population and conservation status of the endangered *Dracaena ombet* tree in dry Afromontane forests

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A R T I C L E I N F O

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A B S T R A C T

Dracaena ombet, a flagship tree species in arid ecosystems, holds a significant ecological, economic, and socio-cultural value. However, its persistence is currently under threat from both anthropogenic and natural factors. Consequently, the species has been listed as an endangered tree species on the IUCN Red List, requiring urgent conservation actions for its continued existence. To develop effective conservation actions, it is necessary to have information on the population dynamics of the species. A study was conducted in the lowland and midland agroecological zones (sites) within the Desa'a dry Afromontane forest, northern Ethiopia to analyze the population status of *D. ombet* and identify its site-specific threats. At each site, abundance, health status, diameter, height and threats of the species were collected using 60 sample plots (20 m × 20 m) distributed over six transects (500 m × 20 m) spaced one km apart. The study showed that the *D. ombet* population was characterized by low abundance and unstable structure. It was further characterized by a substantial number of unhealthy damaged and dead trees. The low abundance of the species with unstable age structure in the dry Afromontane forests can be attributed to various factors such as stem cutting and debarking, leaf defoliation, overgrazing, soil erosion, and competition from expansive shrubs. Alternative livelihood options for the local inhabitants should be introduced to minimize the overexploitation of *D. ombet* for subsistence use in

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the dry Afromontane forests. The impacts of overgrazing and soil erosion on *D. ombet* and its Desa'a habitats should also be addressed through the introduction of community-based exclosures and in-situ soil and water conservation practices, respectively.

1. Introduction

The genus *Dracaena* includes about 160–190 plant species (Govaerts et al., 2021). Some, commonly known as dragon trees, exhibit a tree growth habit (Marrero et al., 1998). Unlike other monocots, tree-like *Dracaena* achieve stem and root thickening due to a secondary thickening meristem (Hubalkova et al., 2017). These trees are mainly found in the tropics. They are native to Africa, but they are also present in Asia, the Mediterranean, central America, and northern Australia (Govaerts et al., 2021). Dragon trees comprise 10 arborescent species (Wilkin et al., 2012), all growing in seasonally arid climates with an annual rainfall of 200–500 mm and mean temperature between 18 and 20 °C (Marrero et al., 1998; Adolt and Pavlis, 2004). Dragon trees are well adapted to capture horizontal precipitation (Nadezhdina et al., 2018) and their distribution is sometimes associated with seasonal cloud forests (De Sanctis et al., 2013; Kalivodová et al., 2020). Dragon trees are threatened by overexploitation, overgrazing and habitat degradation despite their economic and ecological values in dryland areas (Ghazali et al., 2008; Al-Okaishi, 2020; Maděra et al., 2020). The effects of these anthropogenic pressures have been intensified by climate change in the last decade, as highlighted by Elnoby et al. (2017) and Vahalík et al. (2023) in the case of *Dracaena ombet* Kotschy and Peyr. and *D. cinnabari* populations. These populations have also become more scattered with small and isolated patches with unbalanced age structures, where often the tree seedlings are missing (Lengálová et al., 2020; Maděra et al., 2020). As a result, *D. ombet, D. cinnabari*, *D. draco, D. tamaranae* and *D. serrulata* have been listed on the International Union for Conservation of Nature (IUCN) Red List as threatened species (IUCN, 2017) among the total ten dragon trees (Wilkin et al., 2012).

Dracaena ombet is a flagship species of dryland areas of the north-east African region with substantial economic and ecologic benefits. For example, its fruits are edible and eaten by local communities as a supplement to their meagre diets (Ghazali et al., 2008). The fruits and leaves are used as livestock fodder, and resin extracted from its stem is used for traditional medicine (Mohammed, 2015). Furthermore, the species is vital for the livelihood of the local people through the harvest of its plant parts for making household utensils and farm implements (Ghazali et al., 2008; Gidey et al., 2023). It is also valuable for soil and water conservation, carbon sequestration, shade and adaptation to the impacts of climate change (Kamel et al., 2014; Maděra et al., 2020). *D. ombet* is native to Egypt, Sudan, Ethiopia, Eritrea, Somalia, Djibouti and Saudi Arabia (Marrero et al., 1998; Ghazali et al., 2008), typically situated in between 1000–1800 m altitude with an annual rainfall of 200–500 mm (Thulin, 1995; Kamel et al., 2014). However, the current suitable habitats of the species were predicted to contract due to climate change in Ethiopia (Birhane et al., 2023) and Sudan (Andersen et al., 2022).

In Ethiopia, two subspecies of *D. ombet* are found, subsp. *ombet*, which is the focus of this study, and throughout the paper referred to as *D. ombet* occurs in the northern dry Afromontane forests (Aynekulu, 2011), while subsp. *schizantha* is situated on the escarpemnets in eastern Ethiopia to the east of the Rift Valley and northern Somalia (Bos and Teketay, 1997), mainly in open habitats, often in association with the evergreen shrub, *Buxus hildebrandtii* (Kitaba, 2006). Dry Afromontane forest is one of the 14 ecosystem types of Ethiopia and is characterized by a long dry season (October–mid-June). Its average annual temperature varies between 14 and 20 °C and the annual rainfall from 700 to 1100 mm, with most of the rain recorded in mid-June to mid-September (Ethiopian Biodiversity Institute, 2022). The ecosystem is the second most rich vegetation type in the country, and a habitat for a large number of endemic and unique animal and plant species. Despite the substantial values of the ecosystem to humans, it has been deteriorated by various disturbances including overexploitation and land-use change (Aynekulu, 2011; Ethiopian Biodiversity Institute, 2022; Birhane et al., 2023).

The health and population structure of *D. ombet* in dry Afromontane forests is currently impacted by anthropogenic and natural factors (Ghazali et al., 2008; Gidey et al., 2023). For example, in northern and eastern Africa, the local communities harvest intensively the species for making various household materials (Ghazali et al., 2008; WeForest, 2018). They also overgraze its habitats (Kamel et al., 2014; WeForest, 2018). In addition, natural phenomena such as soil erosion and encroachment by expansive shrubs occasionally occur in the species' habitats (Ghazali et al., 2008; Mohammed, 2015; Haile et al., 2021; Gidey et al., 2023). These factors have then led to deforestation and degradation of the remaining populations of the species (Ghazali et al., 2008; WeForest, 2018). Nevertheless, the impacts of anthropogenic and natural pressures on *D. ombet* and other dry Afromontane trees depend on the characteristics of their natural habitats including altitudinal features and edaphic properties (Aynekulu, 2011; Birhanu et al., 2021; Hishe et al., 2021a). For instance, Vahalik et al. (2020) found a larger number of *D. serrulata* trees in the higher altitudes of the Dhofar Mountains of Oman, characterized by low pressures (e.g., livestock grazing) than at the lower altitudes. Similar situations have also been observed for several dry Afromontane trees elsewhere (Aynekulu et al., 2016; Birhanu et al., 2021). Understanding the site-specific (altitude-based) information related to population dynamics and threats may contribute to sustainable conservation of *D. ombet* in dry Afromontane forests (Lengálová et al., 2020; Andersen et al., 2022). This study aims 1) to assess the abundance, health status and population structure of *D. ombet*; 2) to evaluate the relationships between the abundance and health status of the species, and altitude and soil variables; and 3) to determine site-specific threats to the species and its habitats in two agroecological zones, representing different altitudinal gradients. We hypothesized that 1) the abundance, health status and structural characteristics of the species will be higher in the midland areas than the lowlands because of lower level of disturbances in the midland areas, 2) there will be positive correlations between abundance and health status of the species, and altitude and soil variables, and 3) site-specific threats will be identified for each study area due to higher level disturbances in the lowland areas than the midlands.

2. Methods

2.1. Study species

Dracaena ombet Heuglin ex Kotschy & Peyr. (Asparagaceae) is an evergreen, long-lived tree that grows to about 5–8 m height, with a densely packed umbrella-shaped crown (Kotschy, 1867; Brown and Mies, 2012). Its trunk is forked, grey in colour, and divided into several branches, with sword-shaped leaves, about 1 m long and 5 cm wide. The leaves are thick, smooth on the lower and upper surfaces, and erect in position to reduce transpiration (Kotschy, 1867). The inner part of the branches and the roots consist of fiber, this is an indicator that the species can resist drought, and it probably depends on mist and rain fall rather than ground water (Ghazali et al., 2008). As a result, *D. ombet* establishes and grows on shallow, rocky soils where no permanent ground water occurs (Ghazali et al., 2008; Aynekulu, 2011). *D. ombet* has white flowers, and the fruits are spherical flesh berries each containing one to three small seeds (Bauerová et al., 2020). The tree produces seed once per year between April and July. Although seed production may be high, many seeds do not germinate due to lack of viability (Ghazali et al., 2008; Birhane et al., 2023; Gidey et al., 2023). *D. ombet* seeds seem to have a long dormancy period (could be more than a decade) in the soil, which enable them to germinate and establish under favourable conditions (Ghazali et al., 2008). The seeds are manly dispersed by birds (González-Castro et al., 2019), water and wind (Ghazali et al., 2008). Vegetative propagation for *D. ombet* was attempted using axillary buds, but was not successful (Ghazali et al., 2008).

2.2. Study sites

The Desa'a dry Afromontane forest is located in northern Ethiopia, on the border between the Tigray and Afar regions (Fig. 1). The forest lies between 13° 20'–14° 10'N latitude and 39° 32'–39° 55'E longitude, with an altitudinal range between 900 and 3100 m. It covers about 154,000 ha (WeForest, 2018). The forest has high economic, ecological and biodiversity conservation, as well as climate change mitigation and adaptation values at local and global scales (Aynekulu, 2011; WeForest, 2018). For example, it has been a source of livelihood and other ecological services for nearly half a million people (WeForest, 2018). Desa'a was also selected by the Ethiopian government as one of the biodiversity hubs for the implementation of the international climate change mitigation programmes such as the REDD^{+} initiatives (Tetemke et al., 2019).

Desa'a is characterized by varied climate, geology and topography (Nyssen et al., 2005). Altitude is the major influencing factor for the amount of rainfall in the forest area (Nyssen et al., 2005). The average annual temperature ranges between 13 to 25 °C and rainfall is from 400 to 700 mm (Hishe et al., 2021a). The dominant soil types are Leptosols, Cambisols, Vertisols, Regosols and Arenosols (BoANR, 1997). The variability in climate, altitude and edaphic conditions makes the forest an important habitat for about 90 woody

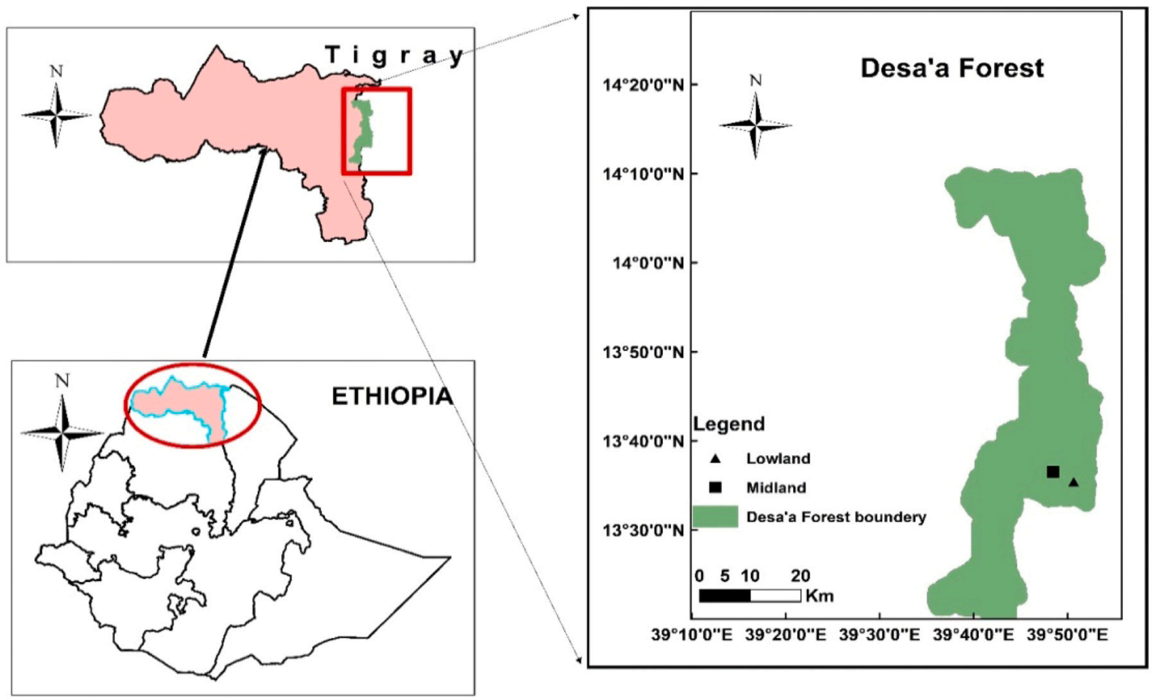

Fig. 1. Geographic locations of the study sites within the Desa'a dry Afromontane forest, northern Ethiopia.

Table 1
Descriptions of indicators used to categorize different threats to *D. ombet* and its habitats in the Desa'a dry Afromontane forest, northern Ethiopia.

Threats	Threat level			
	High	Medium	Low	Absent
Stem cutting	Most trees are badly cut and chopped; cut stumps are visible	Trees are partially damaged with the stem, e.g. branches are cut	Signs are the same with the medium but on the sporadic scale	No signs of cutting
Stem debarking	Most trees are badly debarked	Some trees are sparsely debarked	Trees are rarely debarked	No signs of debark
Leaf defoliation	Trees are badly defoliated; branches are highly detached	Trees are defoliated; branches are detached	Trees are slightly defoliated; branches are detached	No signs of defoliation
Grazing pressure	Cattle and goats are seen; fresh dungs are seen; trampled plants	Dungs at one or two places are seen; hoof-mark is seen	Dungs and hoof may not be visible	No signs of grazing
Fire	Stems are blackened; the crown is burnt, and some trees are dead	Stems are blackened; the crown is burnt, but trees are not dead	Understory vegetation burns are rarely seen	No signs of fire
Soil erosion	Small gullies and exposed roots are seen	Rill erosion is seen	Only surface erosion is seen	No signs of soil erosion
Weed infestation	Weeds occupy more than 50 % of the plot	Weeds occupy about 10–50 % of the plot	Weeds occupy less than 10 % of the plot	No weeds
Shrub encroachment	Shrubs occupy more than 50 % of the plot	Shrubs occupy about 25–50 % of the plot	Shrubs occupy less than 25 % of the plot	No shrubs

plant species including the threatened *D. ombet* and *Dobera glabra* trees (WeForest, 2018). *Juniperus procera* and *Olea europaea* subsp. *cuspidata* are the dominant trees in the highland parts of the forest while *D. ombet* and *D. glabra* dominate the lowlands (Aynekulu, 2011; WeForest, 2018). The forest is also a home for various threatened wildlife species including the hamadryas baboon (*Papio hamadryas*), the spotted hyaena (*Crocuta crocuta*), the African striped ground squirrel (*Xerus erythropus*) and the cinereous bunting (*Emberiza cineracea*) (WeForest, 2018). *Cynodon dactylon* is the major grass species found in the forest and is highly preferred by livestock and wild grazers. Desa'a is one of the few significant remnants protected dry Afromontane forests of Ethiopia, and is among the 58 national forest priority areas designated to conserve biodiversity (Woldemichael et al., 2011). Despite the forest is a protected area, it is highly degraded by overexploitation and land-use change resulting in the reduction of forest cover and biodiversity (Aynekulu, 2011; Giday et al., 2018; Hishe et al., 2021a).

According to Bekele-Tesemma (2007) Ethiopian agroecological zone classifications based on altitude, the Desa'a forest encompasses three zones: lowland (500–1500 m), midland (1500–2300 m) and highland (2300–3200 m) with an area cover of 15 %, 51 % and 34 %, respectively (WeForest, 2018). *D. ombet* is present within the *Vachellia etbaica* communities in Desa'a forest at 1000–2000 m altitude (Aynekulu, 2011; Birhane et al., 2023). At this altitude, two agroecological zones, representing different altitude gradients were selected for this study (Fig. 1). The lowland agroecological zone, hereafter referred to as 'Lowland site' is located at lower altitudes (1000–1500 m) while the midland agroecological zone, hereafter referred to as 'Midland site' is situated at altitude between 1500 and 2000 m. The lowlands are characterized by low amount of rainfall and high temperatures whereas the midlands have medium amount of rainfall and moderate temperatures (Bekele-Tesemma, 2007).

2.3. Sampling design and data collection

The comprehensive land-use map of the Desa'a forest produced by WeForest (2018) and a reconnaissance survey were first used to locate the study agroecological zones. Then, in each zone (site), six parallel transects of 500 m long and 20 m wide (1 ha) set one km apart were established along an altitudinal gradient from the edge of each site. Each transect was divided into 10 plots of 20 m × 20 m set 50 m apart. A total of 60 plots were established at each site. The field inventory was conducted from April to August 2020. In each plot, the abundance of the species was counted, and the diameter at breast height (1.3 m above the ground level – DBH), and the diameter at stump height of living trees (0.3 m above the ground level – DSH, for plants that had a height <1.3 m) were measured using a diameter tape and a calliper, respectively. Height was measured using bamboo stick 5 m long, graduated with 10 cm markings. The health status of the trees was determined through visual observation by comparing living and non-living plant parts. The altitude of each plot was recorded using a hand-held Garmin 74 GPS.

Soil samples were taken from the four corners and the centre of each plot using an 'X' pattern to a 30 cm soil depth (Negash and Starr, 2015). Accordingly, a total of 60 composite soil samples were collected of each site for some soil physical and chemical analysis. Prior to the analysis, the soil samples were cleaned from plant roots and other debris, then air-dried and sieved.

To assess the conservation threats to the species and its habitats, various threat indicators were assessed by observation within the plot (Table 1). These indicators were adopted from various sources (e.g., Aynekulu, 2011; Negussie and Delaet, 2017; Giday et al., 2018; WeForest, 2018; Haile et al., 2021; Gidey et al., 2023).

2.4. Soil analysis

The soil samples were analysed in the soil laboratory of the Department of Land Resource Management and Environmental Protection at Mekelle University in Ethiopia. Soil texture was determined using the hydrometer method (Gee and Bauder, 1982). The pH of the soil was measured with a pH meter in a 1:2.5 soil to water ratio suspension. Electrical conductivity was measured by a conductivity meter in a 1:5 soil to water ratio suspension. Soil organic carbon was analysed using the Walkley and Black methods (Walkley and Black, 1934). Total nitrogen and available soil phosphorus were determined using the Micro-Kjeldhahl and Olsen methods, respectively (Ryan et al., 2001). Exchangeable potassium and cation exchange capacity were determined using the ammonium acetate

Table 2
Soil physical and chemical properties (0–30 cm depth) of the study sites.

Soil parameters	Lowland site Mean (±SEM)	Midland site Mean (±SEM)
Sand (%)	63 (±6.6)	67 (±8.2)
Clay (%)	19 (±5.5)	18 (±6.2)
Silt (%)	17 (±4.4)	17 (±4.8)
Soil pH (1:2.5 H_2O)	8.4 (±2.8)	8.0 (±3.2)
EC (1:5 H_2O)	0.16 (±0.5)	0.16 (±0.6)
OC (%)	2.35 (±0.7)	2.55 (±0.8)
TN (%)	0.20 (±0.2)	0.28 (±0.3)
Av. P (ppm)	5.46 (±2.2)	5.66 (±2.4)
Ex. K (ppm)	306 (±10.8)	300 (±11.0)
CEC (meq/100 g)	26.38 (±7.8)	24.4 (±7.2)

EC = electrical conductivity, OC = organic carbon, OM = organic matter, TN = total nitrogen, Av. P = available phosphorus, Ex. K = exchangeable potassium, CEC = cation exchange capacity method (Van Reeuwijk, 1993). Soil physical and chemical properties of the study sites are presented in Table 2.

2.5. Data analysis

To analyse the abundance at each site, the *D. ombet* trees were divided into three ontogenetic stages based on findings from previous studies and opinions of the local communities (Ghazali et al., 2008; Andersen et al., 2022; Birhane et al., 2023). 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 = 1.3–1.5 m) and mature trees (DBH > 8 cm and height >1.5 m). The health status of each tree or sapling was categorized as healthy (70 % of the tree parts were living), moderately healthy (35–70 %), unhealthy (1–35 %) or dead (0 %) (Ghazali et al., 2008). The species' population structure was further characterized graphically using size-class distributions (SCDs). The density (e.g., the total density, the densities of seedlings, saplings, and mature trees) and the health status of the species between the sites were compared using the Kruskal-Wallis nonparametric test as the data did not meet the assumption of normality. The health status was further analysed using descriptive statistics such as percentages. To assess the correlation between the species' abundance and health status, as well as altitude and soil variables (Table 2), Spearman's correlation analysis was performed. Significant differences were considered at $p < 0.05$. The Statistical Analysis Software (SAS) version 9.2 was used for data analysis. The conservation threats for the species and its habitats were categorized into high, medium, low, and absent levels according to the corresponding indicators presented in Table 1.

3. Results

3.1. Abundance, health status and structure

The total density of *D. ombet* ranged from 173 to 235 trees ha^{-1}, with a significantly higher value recorded in the midland site (Table 3). The mean density in the sites was 204 ± 4.2 trees ha^{-1}, with a relatively higher number of mature trees than saplings and seedlings. As to the health status, about 47 % of trees were healthy and the remaining 27 % and 26 % were unhealthy and dead, respectively (Table 3). Tree health was not significantly different between the sites (Table 3). The SCDs highlighted that the population lacked regeneration, seedlings (DSH <2 cm) and saplings (e.g., DBH between 2 to 5 cm) (Fig. 2). The highest individuals were found in stem diameter class of 20–25 and 15–20 cm, respectively. Besides, the upper SCDs were characterized by a dearth of mature trees (DBH > 25 cm) (Fig. 2).

3.2. Effects of altitude and soil variables

The density of *D. ombet* was significantly positively correlated with altitude, silt soil particles, soil organic carbon and soil nitrogen. However, tree density was negatively correlated with the sand fraction of the soil, soil pH, available phosphorus and exchangeable potassium. The correlations between the tree health status and soil nitrogen were positive while the correlations of the tree health with clay fraction and soil pH were significantly negative (Table 4).

3.3. Conservation threats

At the sites, *D. ombet* and its habitats were severely threatened by stem cutting and debarking, leaf defoliation, overgrazing, soil erosion and competition from expansive shrubs (Table 5; Fig. 3). However, the effects of weed infestation and fire on the tree and its habitats appeared to be minor (Table 5). Intensive cutting, debarking and defoliation of the trees by local communities were observed during the period of sampling. We found 30 *D. ombet* trees ha^{-1} felled, 20 trees ha^{-1} defoliated and 18 trees ha^{-1} partially debarked. Cattle, goats and camels have also been seen browsing and trampling on the species. In addition, multiple small gullies and rills were often seen around the root zones of the species. Expansive shrubs of *Cadia purpurea* and *Tarchonanthus camphoratus* were the major encroaching of the species' habitats.

Table 3
Density and health status (trees ha^{-1}) of *D. ombet* in the study sites.

Parameters	Lowland site Mean (±SEM)	Midland site Mean (±SEM)	Both sites Mean (±SEM)
Total density	182^b (±4.6)	225^a (±3.9)	204 (±4.2)
Seedlings	0^a (±0.0)	0^a (±0.0)	0 (±0.0)
Saplings	24^b (±2.8)	45^a (±3.2)	35 (±3.0)
Mature trees	158^b (±4.5)	180^a (±4.8)	169 (±4.6)
Healthy trees	29^a (±2.4)	36^a (±3.0)	34 (±2.7)
Moderately healthy trees	56^a (±2.5)	66^a (±2.8)	61 (±2.6)
Unhealthy trees	50^a (±4.2)	61^a (±4.5)	55 (±4.3)
Dead trees	47^a (±6.0)	62^a (±5.6)	54 (±5.8)

Within the same rows, the means with the same letters are not significantly different at $p < 0.05$. SEM = standard error of the mean.

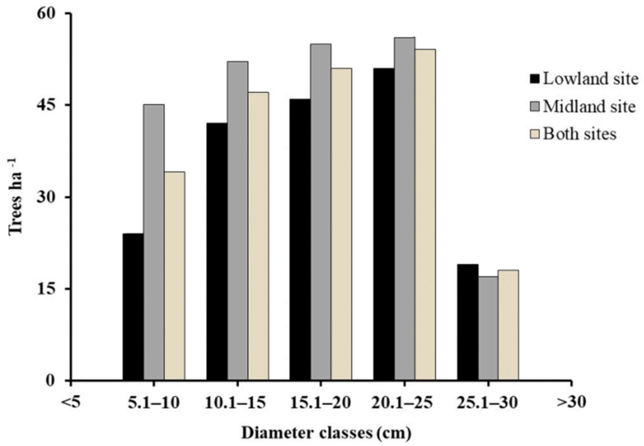

Fig. 2. DBH size-class distributions of *D. ombet* populations in the Desa'a dry Afromontane forest, northern Ethiopia.

Table 4
Correlations of the density and health status of *D. ombet*, with altitude and soil variables (the two sites were pooled together).

Parameters	*D. ombet* total density (trees ha^{-1})	*D. ombet* healthy trees (trees ha^{-1})
Altitude (m)	0.77 *	0.29
Sand (%)	–0.11	0.03
Clay (%)	0.20	–0.15
Silt (%)	0.23 *	0.18
pH	–0.15	–0.01
EC	0.15	0.07
OC (%)	0.16 *	0.14
TN (%)	0.17 *	0.22 *
Av. P (ppm)	–0.11	0.07
Ex. K (ppm)	–0.05	0.21
CEC (meq/100 g)	0.12	0.19

EC = electrical conductivity, OC = organic carbon, TN = total nitrogen, Av. P = available phosphorus, Ex. K = exchangeable potassium, CEC = cation exchange capacity.
* = indicated significant effects at $p < 0.05$.

Table 5
Impacts of different conservation threats on *D. ombet* and its habitats in the Desa'a dry Afromontane forest, northern Ethiopia.

Threats	Lowland site				Midland site			
	High	Medium	Low	Absent	High	Medium	Low	Absent
Stem cutting	✓				✓			
Stem debarking	✓				✓			
Defoliation	✓				✓			
Overgrazing	✓				✓			
Fire			✓				✓	
Soil erosion	✓				✓			
Weed infestation			✓				✓	
Shrub encroachment	✓				✓			

4. Discussion

Results showed that the *D. ombet* populations in the lowland and midland areas of Desa'a dry Afromontane forest were characterized by low abundance and unstable population structure. The latter is evinced by lack of regeneration, seedlings (DSH < 2 cm) and mature trees (DBH > 25 cm). About half the number of trees was unhealthy or dead. This low abundance and unstable structure was mainly due to the overexploitation of mature trees (DBH > 8 cm) – stem cutting and debarking as well as leaf defoliation. For example, the local communities harvested intensively the mature trees for subsistence income. Namely, they collected their stems, bark and leaves for preparing household and agricultural implements to be sold in the local markets. These threats in combination with other pressures (e.g., overgrazing and soil erosion) are believed to have been affecting the species in the Desa'a forest for a long time and may

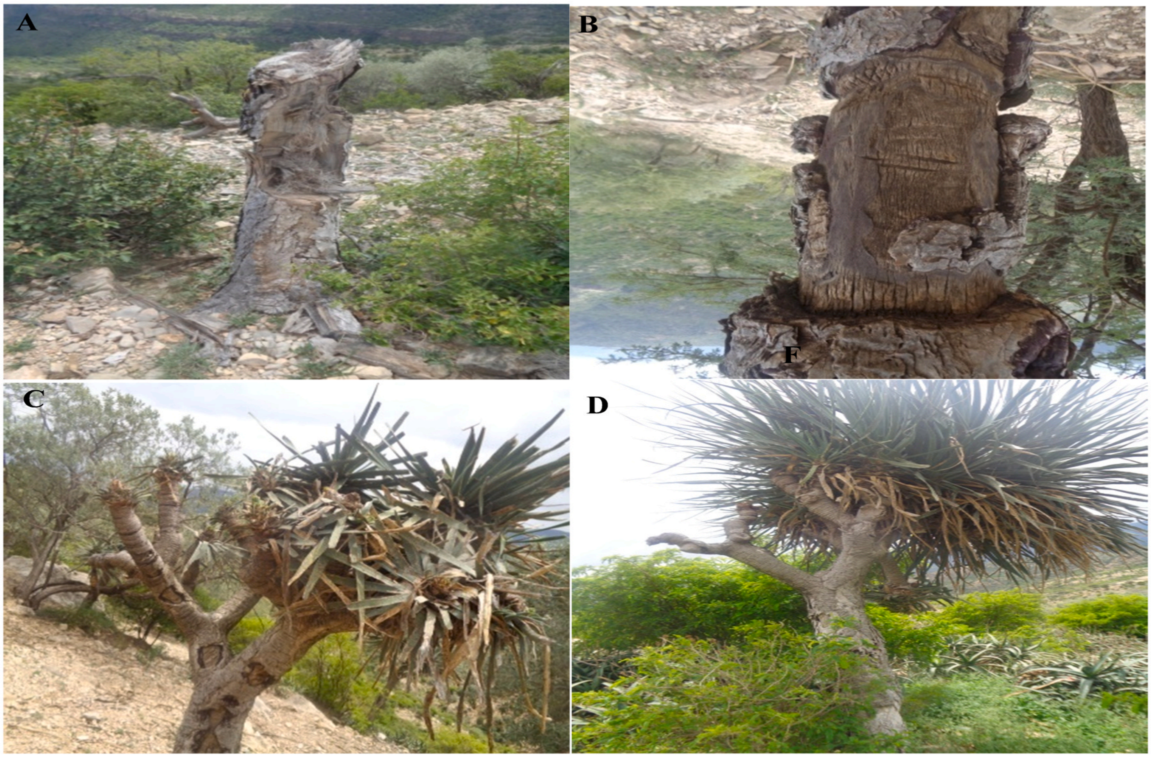

Fig. 3. Different threats to *D. ombet* and its habitats in the Desa'a forest: A) Stem cutting, B) Stem debarking, C) Defoliation and D) Encroachment by expansive shrubs (Gidey et al., 2023).

threaten persistence of the population (WeForest, 2018; Aynekulu, 2011; Hishe et al., 2021b) and to be dominated by old trees (Lengálová et al., 2020) which where only confined to small eroded areas (Aynekulu, 2011). Similarly, mature trees of the species have been heavily exploited for rope making and fodder in Egypt and Sudan (Kamel et al., 2014; Mohammed, 2015). Consequently, the abundance and health status of the species were severely impacted. For instance, a detailed inventory of the trees in the Red Sea Hills, Egypt recorded a total of 353 mature trees, 54 % of which were unhealthy. Its population structure was also very unstable as there was no regeneration (Ghazali et al., 2008; Kamel et al., 2014). Overexploitation of *D. ombet* impacted its persistence in various ways including decrease in the number of mature trees, or compromised health of mature trees, both of which may compromise seed production (Ghazali et al., 2008).

Results also showed that saplings of the species were browsed and trampled by cattle, goats and camels in the Desa'a forest. Local communities also over-defoliate the mature trees for livestock feed, particularly during drought periods. These pressures increase the vulnerability of the saplings and mature trees to soil erosion, disease and pests (Ghazali et al., 2008; Elnoby et al., 2017). Overgrazing habitats of the species was also identified as the major factor for the poor regeneration and high seedling mortality for *D. ombet* and other woody species in the Desa'a forest. It reduces the number of viable seeds on the soil surface and of emerged seedlings (Giday et al., 2018; WeForest, 2018; Hishe et al., 2021a). Similarly, in Egypt, particularly in the Gabel Elba areas, overgrazing habitat of the species threatened severely the regeneration and seedlings of the species (Ghazali et al., 2008; Kamel et al., 2014). Moreover, goat overgrazing was found as a key factor for *D. cinnabari* seedlings mortality in the island of Socotra, Yemen (Maděra et al., 2018). Overgrazing by livestock was also mentioned elsewhere as the major pressure for the low regeneration and seedling growth for other dragon trees, e.g., *D. tamaranae* (Almeida and Censo, 2003) and *D. serrulata* (Vahalik et al., 2020).

The study recorded a substantial number of small gullies and rills around the root zones of *D. ombet* and its habitats. These could be due to the frequent runoff and soil erosion that occurred in the Desa'a forest (Negussie and Delaet, 2017; WeForest, 2018; Hishe et al., 2021a). Soil erosion significantly impacted the regeneration and overall growth of the woody species in the Desa'a forest including *D. ombet*. It washes away their viable seeds from natural habitats, uprooting the established small seedlings and leaching out important soil nutrients (Berihu et al., 2017; WeForest, 2018). Similar findings confirmed that soil erosion reduced substantially the *D. cinnabari* seedlings' growth in the island of Socotra, Yemen (Pietsch et al., 2013). The same observations were also recorded for other tree species in Afromontane forests in northern Ethiopia (Aynekulu et al., 2016; Birhanu et al., 2021).

The expansive light-demanding *C. purpurea* and *T. camphoratus* pioneer shrubs are the major invaders of *D. ombet* habitats. This result agrees with previous studies conducted in the Desa'a forest. For example, Haile et al. (2021) and Hishe et al. (2021b) found that the aforementioned shrubs were the key encroachers of the high- and midland portions of the forest that negatively threaten the overall growth of the climax tree species such as *J. procera* and *O. europaea* subsp. *cuspidata* through competing for soil resources (e.g., water and nutrients). These shrubs are also expected to decrease the diversity and composition of the remnant Desa'a forest via their rapid colonization capacity and ability to produce plenty of high-quality seeds for regeneration (Aynekulu, 2011; Haile et al., 2021). A similar finding was also reported on the rapid colonization of *C. purpurea* in the Girat Kahisu Hugumburda forest, in northern Ethiopia (Aynekulu et al., 2016). On the other hand, some shrub species can serve as nurse plants allowing the *D. cinnabari* seedlings to survive under grazing pressure (Rejžek et al., 2016).

The abundance of the species was influenced by altitude and soil properties. This is consistent with previous studies on various dry Afromontane trees in northern Ethiopia (Aynekulu, 2011; Birhanu et al., 2021; Hishe et al., 2021a). At the sites, the most important factors affecting the density of the tree were altitude and amounts of silt, organic carbon and nitrogen in the soil. Overall density of the tree was higher in the midland site than in the lowland. This could be due to the former site receiving higher annual rainfall and horizontal precipitation (Kalivodová et al., 2020). This result agrees with Vahalik et al. (2020) who recorded different densities of *D. serrulata* trees in three areas within the Dhofar Mountains of Oman, at different altitudes. The Jabal Samhan area, characterized by relatively higher altitudes (1075–1579 m) and moderate rainfall included 1835 trees while the Jabal al Qamar area characterized by lower altitudes (659–1082 m) and rainfall had only 552 trees. However, tree health showed a non-significant difference between the two sites. This could be associated with the uniform occurrence of the threats for the species at the sites, regardless of their altitudinal differences. This result is consistent with Kamel et al. (2014) who recorded a total of 353 *D. ombet* trees in the Gabel Elba, Egypt , 54 % of which were unhealthy, and distributed more or less evenly over the tree's preferred habitats.

This study and other recent studies (e.g., WeForest, 2018; Lengálová et al., 2020) evidenced that *D. ombet* is currently under endangered conditions due to anthropogenic and natural factors, which threaten its populations in dry Afromontane forests. Urgent conservation actions are then necessary to maintain its existence. For instance, the overexploitation of the tree for subsistence use should be minimized by introducing alternative livelihood strategies. In the Desa'a forest, various environmentally friendly and non-destructive alternative livelihoods have been suggested, including the gathering of non-timber forest products (e.g., medicinal plants, edible fruits and honey production), poultry farming and home gardening (Tamba et al., 2021; Gidey et al., 2023). Overgrazing of *D. ombet* habitats can also be reduced by introducing livestock exclosures. The latter are critical to enhance the conservation of the species as it improves the microclimate of the area, increasing the abundance of viable seeds for regeneration and protecting the emerged small seedlings (Ghazali et al., 2008; Tamba et al., 2021). Moreover, the degradation of Desa'a forest by soil erosion and runoff can be minimized through community-based construction of soil and water conservation structures like in-situ micro basines, deep and shallow trenches and terraces. These strategies may contribute to ecological restoration of the forest and succession of its threatened tree species like *D. ombet* and others via improving soil fertility and moisture retention (Negussie and Delaet, 2017). The impacts of the expansive shrubs on *D. ombet* and its Desa'a habitats should also be addressed, namely by using them for preparing biochar and bioenergy feedstocks (Haile et al., 2021) or as a substitute of local fuel wood instead of other native tree species (WeForest, 2018).

5. Conclusions

This research showed that the prevailing *D.ombet* populations in the Desa'a dry Afromontane forest of northern Ethiopia are characterized by low abundance and unstable structure. It also revealed that about 53 % of the prevailing populations were unhealthy and damaged. The low abundance, unstable structure and poor health status were primarily due to stem cutting and debarking, leaf defoliation, overgrazing, soil erosion and competition from expansive shrubs. Therefore, to achieve sustainable *D. ombet* conservation in dry Afromontane forests, it may be crucial to implement conservation measures that address both anthropogenic and natural factors. This can be achieved through a combination of community engagement and policy interventions. To reduce the overexploitation of the species, different measures such as the use of available alternative livelihoods (e.g., collecting non-timber forest products, poultry farming) should be introduced. Livestock overgrazing within the species habitats should also be minimized through the introduction of community-based exclosures. Furthermore, the impacts of soil erosion and of the expansive shrubs on *D.ombet* and its Desa'a habitats should be addressed via the construction of soil and water conservation structures and the introduction of proper utilization techniques, respectively. Future research should focus on studying the species habitat preferences and reproductive biology. This knowledge can inform the development of targeted conservation actions, such as habitat restoration and assisted regeneration and seedling growth techniques.

CRediT authorship contribution statement

Gidey Tesfay: Writing – review & editing, Writing – original draft, Resources, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Birhane Emiru:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Solomon Negasi:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Atsbha Tesfay:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Manaye Ashenafi:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Hishe Hadgu:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Gufi Yirga:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Tesfaye Musse:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Negussie Aklilu:** Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Oliveira Tânia Sofia:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Palma Joao HN:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Madĕra**

Petr: Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Borges Jose G:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

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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