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Causes and consequences of mother tree population decline in Fazara Natural Forest Reserve, Sudan

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Abstract

Although recent progress has been made in exploring and understanding tree population ecology and factors that disturb its development and dynamics, other pivotal research gaps remain untouched. Causes and consequences of mother tree decline, a seed-producing source and biodiversity niche, are at the core of these gaps. We bridged this gap by analyzing the status of mother trees, dendrometric parameters, stand parameters, and factors driving changes in species composition at Fazara natural forest reserve, across 74 samples of 1000 m^2, systematically distributed in the high and lowland sites of the forest. To run the analysis, we respectively used ANOVA, paired-sampled t-test, post hoc test, and cross-tabulation in JAMOVI, Minitab, and SPSS. Findings showed that the abundance of mother trees, saplings, and seedlings were twice and three times higher in highland sites than lowland ones, respectively ($F_{1,72}$ = 141.2 and P = 0.03; $F_{1,72}$ = 128.3 and P = 0.01; $F_{1,72}$ = 116.5 and P < 0.001, respectively). While juvenile trees displayed no significant differences between the sites ($F_{1,72}$ = 162.4 and P = 0.06). Illegal harvesting was the principal contributor to mother tree decline, where stumps and debranched trees density at lowland sites were four and three times that of highland sites, respectively. However, deterioration of species richness, regeneration, and abundance were the common consequences of mother trees decline in the reserve. Interventions through restriction of trespassing, awareness-raising, and patrolling guards are urgently needed to protect both mother and juvenile trees.

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Introduction

Mother and old trees represent the key iconic biota in most terrestrial ecosystems worldwide (Lindenmayer & Laurance, 2017). They form a foundation for habitat diversity (Asbeck *et al.*, 2021), niche complexity (Derroire *et al.*, 2016; Gebru *et al.*, 2019), seeds production and seedlings recruitment for most seedly regenerated tree species in tropical, subtropical and temperate forests, as well as savannas, pastures and urban environments (Domene *et al.*, 2017; Kutnar *et al.*, 2019). They significantly guide the spatial and temporal allocation and distribution of their newly recruited individuals and other related plant and animal species found in natural forests and rangelands (Asigbaase *et al.*, 2019; Ghanbari *et al.*, 2021; Mohammed *et al.*, 2021). In addition to that, they play essential functions in nutrient cycling, weather acclimatization, recreation sites, and carbon sequestration, as well as provision of food, feed, and medicine (Adam *et al.*, 2013; Ibrahim *et al.*, 2018; Neya *et al.*, 2019). However, the sustainability of these roles and functions is of high significance to Africa particularly, the natives of sub-Sahara countries and Sahel region (Marone *et al.*, 2017; Ouédraogo *et al.*, 2019).

In Africa, the contribution of forest trees to rural communities livelihood is high, especially in marginalized areas and conflicted sites (Deafalla *et al.*, 2014; Suleiman *et al.*, 2017). This contribution clearly observed in the eastern and southern parts of Sudan, where trees and their by-products support more than 60% of the local community's needs and represent the main source of income regeneration (Adam *et al.*, 2013; Mahgoub, 2014; Mohammed *et al.*, 2021). However, such utilization needs to be regulated and properly managed to avoid the decline and depletion of these valuable resources (Gebrehiwot & Hundera, 2014; Ibrahim & Hassan, 2015; Tsegu, 2019). Moreover, for a good yield regulation plan, restoration program, or sustainable management of forest and tree resources, up-to-date information on its juvenile and adult trees population, species composition, as well as seeds production, dispersal, and seedlings establishment, is indispensably required (Gustafsson *et al.*, 2012; Masuku & Xaba, 2013; Owusu *et al.*, 2021).

Different studies had filled the gaps associated with growth and development of herbaceous plants in Sudan and other savannas environments (Dayamba *et al.*, 2008; Gebrehiwot & Hundera, 2014; Hassan & Tag, 2017), the status of seedlings and saplings of woody plants in their natural forests and rangelands (Ali *et al.*, 2015; Hanief *et al.*, 2016; Hasoba *et al.*, 2020; Maua *et al.*, 2020), as well as the species richness, abundance, and uses (Kikoti &mLigo, 2015; Nacoulma *et al.*, 2016). However, information on the status of mother trees and how the observed dramatic human population growth can affect its population is lacking. The current study addressed this gap by assessing the status of mother trees in Fazara natural forest reserve towards the sustainable management of tree resources in the area.

Fazara Natural Forest Reserve (FNFR) is among the largest forest reserves in the eastern part of the Gedaref State at Basunda locality (Mahgoub, 2014; Mohammed, 2019). It is located close to Fazara and Karima villages and forms the only source for wood, edible fruits, medicinal products, grazing areas, and recreation sites for these villages' residents (Hassan, 2019; Mohammed, 2019).

The usual income generation activities of the people around FNFR are agriculture, livestock keeping, non-timber forest products trade, and charcoal production (Ahmed, 2005; Elmekki, 2008; Hassan, 2015). While local community is mainly depending on this reserve (Mahgoub, 2014; Mohammed, 2019), information on its growing stock, adult to juvenile ratio, species richness, and the change driving factors are limited. Additionally, data on the status of the mother tree population, the main source of seeds and new seedlings, and whether it is stable or declining is unknown. Therefore, exploration of the tree population structure in FNFR is a core process to achieve the sustainable management of the forest, which will conserve its multiuse and vulnerable tree species and fulfills the local community needs.

The study hypothesized that areas close to the villagers' settlements (lowland sites) had fewer mother trees and new regeneration compared to remote and mountainous areas (highland sites).

Moreover, as most locals are agro-pastoralists and charcoal producers, we predicted that livestock grazing and illegal harvesting are the main drivers of species composition change in FNFR. Furthermore, we expected that the population of native broadleaved tree species had been severely affected by illegal harvesting and limited individuals remain alive. Besides that, as information on mother and seed-producing trees are scarce, the findings of this study will form a baseline and guide for the decision-maker and natural reserves management to formulate a comprehensive management plan that ensures the regular provision of goods and services, as well as natural restoration and stands maintenance.

Materials and methods

Study area

Fazara natural forest reserve is located at 12° 41′ 00″ N, 12° 48′ 00″ N, 35° 37′ 00″ E, and 35° 44′ 00″ E (Fig. 1), and covers an area of 7,095.9 ha (Hassan, 2015; Mohammed, 2019). It hosts more than 15 tree and shrub species with various perennial plants and grasses, distributed randomly across the mountainous and flatland sites of the reserve (Hassan, 2019; Mohammed, 2019). While the mountainous sites are dominated by *Anogeissus leiocarpus*, *Terminalia brownii*, *Terminalia laxiflora*, *Lannea fruticosa*, *Sterculia africana*, *Ziziphus spina-christi*, and *Pterocarpus lucens* tree species, the flatland sites are dominated by *Acacia seyal*, *Acacia senegal*, *Balanites aegyptiaca*, and *Combretum hartmannianum* (Hassan, 2019).

Moreover, based on the analyzed meteorological data received from Sudan Meteorological Authority (SMA), the average minimum and maximum temperatures, as well as rainfall, were 26 °C, 41 °C, and 700mm, respectively (Figs. 2 and 3). The flat and semi-flat lands of FNFR are characterized by cracky clay and sandy-clay soil types, while the mountainous areas were dominated by sandy soil and rocks (Hassan & Tag, 2017; Mohammed & Hashim, 2015).

Data collection

To inventory the growing stock, population composition, and richness of tree species in FNFR, the study used a systematic sampling technique to establish eleven survey lines across the stratified sites of the reserve (Fig. 1). We stratified the study area into high and lowland sites based on their topographical characteristics (Plates 1 and 2). While the high land sites of FNFR cover its mountainous and hilly areas, the lowland ones encompass its flat and semi-flat lands (Gebru *et al.*, 2019; Mohammed *et al.*, 2021). The seventy-four (74) rectangular sample plots of 25 m x 40 m (1000 m²) were laid across the high and lowland sites of the forest to assess their dendrometric and stand parameters. After marking the sample plot boundary and identifying its hosted tree species, we classified them into mature trees, saplings, and seedlings as recommended by (Derroire *et al.*, 2016; Lindenmayer & Laurance, 2017).

We further divided the mature trees into mature and over-mature ones (mother trees) based on their diameter at breast height (diameter measured at 1.3 m above ground level). We considered seedlings and saplings as woody plants with diameters of < 3 cm and 3 to < 7cm, while mature and mother trees are of ≥ 7 to 30 cm and > 30 cm diameters, respectively (Gebrehiwot & Hundera, 2014; Kikoti *et al.*, 2015; Ligate *et al.*, 2019).

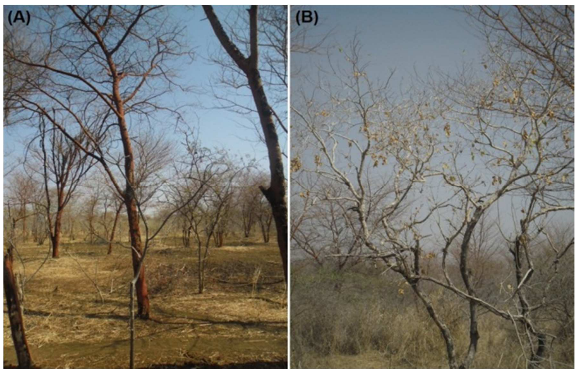

Plate 1. The lowland sites of FNFR; (A) dominated by *Acacia seyal*, and (B) dominated by *Combretum hartmannianum* tree species.

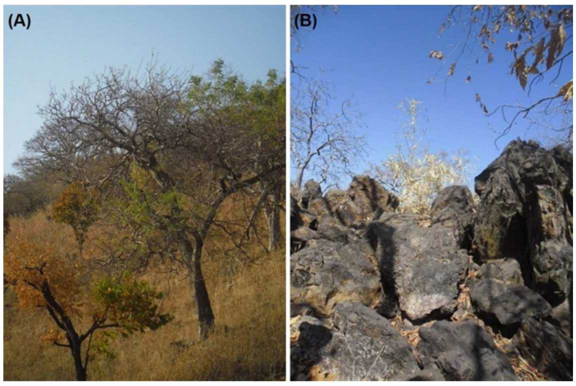

Plate 2. The highland sites of FNFR; (A) dominated by *Terminalia brownii* and *Sterculia africana*, and (B) rocky area.

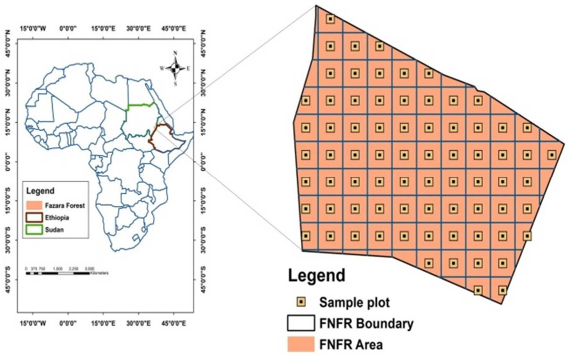

Fig. 1. The map of Fazara natural forest reserve showing the geographic location of the study area and the inventoried sample plots.

While tree diameter at breast height (DBH) was measured using an Ordinary caliper for small trees and diameter tape for large ones (Endale *et al.*, 2017; Tetemke *et al.*, 2019), Vernier caliper was used for seedling and sapling diameters measurements in high and lowland sites of the study area (Hanief *et al.*, 2016; Ligate *et al.*, 2019; Maua *et al.*, 2020; Mohammed *et al.*, 2021). Moreover, a hypsometer was used for total tree height measurements as recommended by other researchers (Ghanbari *et al.*, 2021; Hassan *et al.*, 2022; Mohammed *et al.*, 2021). Additionally, we measured tree crown width using measuring tape at eight directions radiating from the tree base towards its crown edge perpendicular to the surveyor (Ibrahim *et al.*, 2015; Mohammed *et al.*, 2021).

In each 1000 m^2 sample plot, we gathered information on anthropogenic activities like livestock grazing and browsing, stem debarking and crown debranching, tree logging and charcoal production, and intensive seeds (fruits) collection (Chaudhary *et al.*, 2016; Guedje *et al.*, 2016; Nndwammbi *et al.*, 2018; Paulo & Tomé, 2017). All monitored animals were recorded, as well as, the debarked, debranched, and logged trees. Furthermore, we calculated the severity of debarking, debranching, and logging activity as the number of damaged stem to the total number of stems in the plot (Brodie *et al.*, 2015; Ji *et al.*, 2017; Mohammed *et al.*, 2021).

To gather socio-economic data about the reserve, we distributed 240 questionnaires on the residents of Fazara and Karima villages and interviewed 50 key informants (Angelsen, 2012; Fahmi *et al.*, 2018). The key informant interviews covered local leaders, forest officers, rangeland officers, mechanized-farming management officers and the directors of active nongovernmental organizations in the area (Hassan, 2019; Mohammed, 2019).

Data analysis

Mother trees, juvenile trees, saplings, and seedlings abundance were assessed as the number of stems per sample, as recommended by (Endale *et al.*, 2017; Fakhry *et al.*, 2020; Ghanbari *et al.*, 2021). To compute the basal area, volume, relative abundance, relative dominance, relative frequency, and importance value index of various tree species in the high and lowland sites of the reserve, we used the formulae listed in table 1 (Abdou *et al.*, 2016; Gebeyehu *et al.*, 2019; Idrissa *et al.*, 2018; Mohammed *et al.*, 2021). The species dominance and frequency were expressed as species coverage per area and as the presence or absence of the species per area, respectively (Hasoba *et al.*, 2020; Lempesi *et al.*, 2017; Mohammed *et al.*, 2021). Further, we calculated the species richness as the total number of species reported at each site (Asigbaase *et al.*, 2019; Kutnar *et al.*, 2019; Mohammed *et al.*, 2021). To compare the species richness, dendrometric and stand parameters between sites, we used a paired-sampled t-test in Minitab and ANOVA in JAMOVI, respectively (Kingazi *et al.*, 2020; Mohammed, 2019; Mohammed *et al.*, 2021).

A similar procedure was applied to compare the change driving factors across the sites, including the debarking, debranching, logging, and root damages.

Table 1. The equations used to compute basal area, volume and importance value index of the tree species assessed in the high and lowland sites of Fazara natural forest reserve.

Equation	Reference
Basal area (g) = $\frac{\pi * (Diameter\ at\ breast\ height)^2}{4}$	(Ghanbari *et al.*, 2021)
Volume (Vol) = Basal area*Height*Form Factor	(Ligate *et al.*, 2019)
Relative abundance (RA) = $\left(\frac{Species\ abundance}{Total\ abundance\ for\ all\ species}\right) * 100$	(Mohammed *et al.*, 2021)
Relative dominance (RD) = $\left(\frac{Species\ coverage}{Total\ coverage\ for\ all\ species}\right) * 100$	(Assogbadjo *et al.*, 2010)
Relative frequency (RF) = $\left(\frac{Species\ frequency}{Total\ frequency\ for\ all\ species}\right) * 100$	(Idrissa *et al.*, 2018)
Importance value index (IVI) = RA + RD + RF	(Maua *et al.*, 2020)

All descriptive statistics, normality and homogeneity tests have been respectively performed in SPSS (version 26) and JAMOVI (version 1.1.17), as recommended by (Gessesse *et al.*, 2016; Missanjo *et al.*, 2015; Suleiman *et al.*, 2017). Moreover, questionnaires and interview data were sorted, coded, and analyzed in SSPS using one-way ANOVA and cross-tabulations (Burman *et al.*, 2018; Jayakumar & Nair, 2013; Sukhbaatar *et al.*, 2019).

To trace the significant differences between various variables and parameters within and across the sites, we applied Tukey's post hoc test with α = 0.05 (Burman *et al.*, 2018; Mohammed *et al.*, 2022). Furthermore, we classified the regeneration status into good, fair, poor, and none, as guided by (Arosa *et al.*, 2017; Dibaba *et al.*, 2020; Gebeyehu *et al.*, 2019; Mohammed *et al.*, 2021). Good if seedlings > saplings > adults, fair if seedlings > saplings ≤ adult, poor if no seedlings, and none if no seedlings and saplings.

Results

Mother trees abundance and adult to juvenile ratio

Mother trees abundance in highland sites was double that of lowland ones, with significant differences between the sites ($F_{1,72}$ = 141.2 and P = 0.03, Fig. 4). While juvenile trees illustrated no significant differences between the sites ($F_{1,72}$ = 162.4 and P = 0.06, Fig. 4), saplings and seedlings were twice and three times higher in highland sites than lowland sites, respectively ($F_{1,72}$ = 128.3 and P = 0.01; $F_{1,72}$ = 116.5 and P < 0.001, respectively, Fig. 4).

Moreover, the study results displayed that the proportion of the five top tree species significantly differed for mother trees ($F_{1,72}$ = 91.3 and P = 0.04), juvenile trees ($F_{1,72}$ = 101.2 and P = 0.01), saplings ($F_{1,72}$ = 87.4 and P = 0.01), and seedlings ($F_{1,72}$ = 131.3 and P = 0.001) between the high and lowland sites, with a low frequency of seedlings, saplings, and mother trees in lowland sites compared to highland ones (Fig. 5). *Acacia senegal* and *Acacia seyal* have the highest juvenile trees percent compared to *Combretum hartmannianum* and *Ziziphus spina-christi*, which have better seedlings and saplings percentages (Fig. 5).

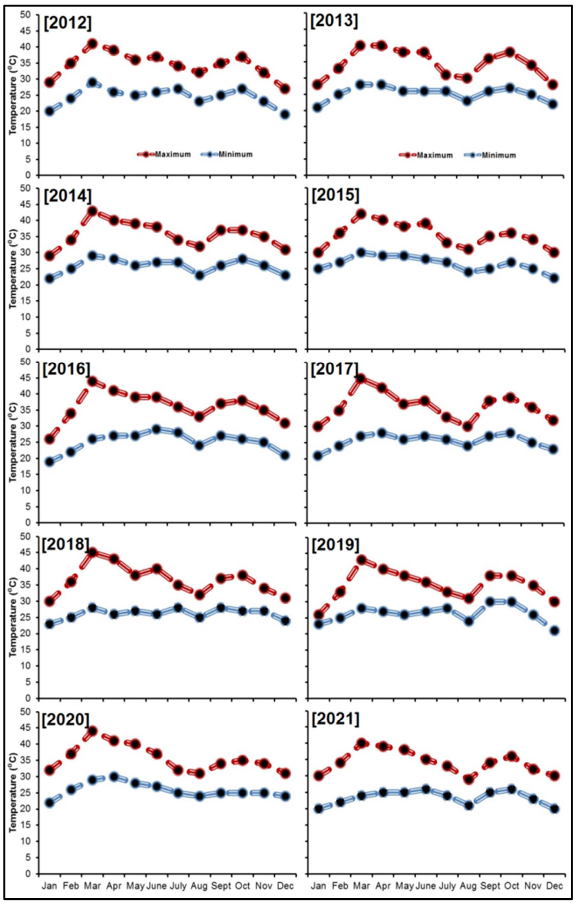

Fig. 2. Mean maximum and minimum temperatures for FNFR (2012 – 2021) that computed based on the data acquired from Sudan Meteorological Authority.

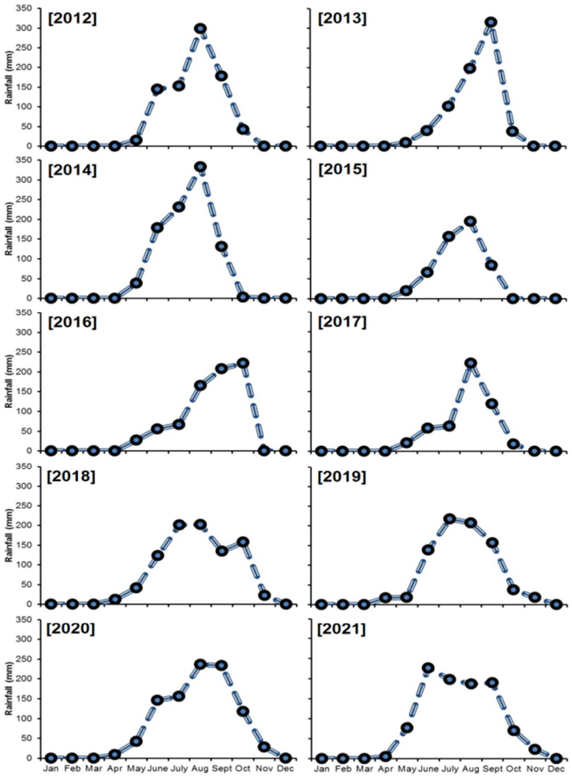

Fig. 3. Mean rainfall for FNFR (2012 – 2021) that computed based the data acquired from Sudan Meteorological Authority.

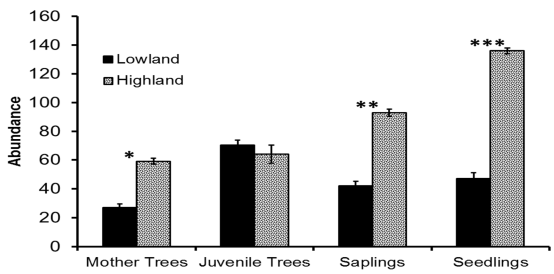

Fig. 4. Mean (±SE) abundance per plot for mother trees, juveniles, saplings, and seedlings inventoried in the low and highland sites of Fazara natural forest reserve. Asterisks on the bars display the significant differences between the sites based on Tuckey Post Hoc test as * = $P \leq 0.05$, ** = $P \leq 0.01$, and *** = $P \leq 0.001$.

Characteristics of dendrometric parameters and regeneration status

The highland sites showed the highest values of tree crown width (m) with significant differences across the sites especially for *Combretum hartmannianum*, *Balanites aegyptiaca*, *Lonchocarpus laxiflorus*, and *Ziziphus spina-christi* (Fig. 6). Moreover, the diameter at breast height (cm) and basal area (m²) of *Balanites aegyptiaca* and *Ziziphus spina-christi* in highland sites were double that of lowland sites ($F_{1,72}$ = 118.7 and $P < 0.01$; $F_{1,72}$= 81.3 and $P < 0.01$; $F_{1,72}$ = 128.1 and $P = 0.01$; $F_{1,72}$= 101.3 and $P = 0.01$, respectively), as well as that of *Acacia senegal* (Fig. 7). However, *Combretum hartmannianum* exhibited the highest tree height and volume values throughout the forest, with significant differences between the high and lowland sites ($F_{1,72}$ = 78.9 and $P < 0.01$; $F_{1,72}$= 86.7 and $P = 0.01$, respectively, Fig. 7).

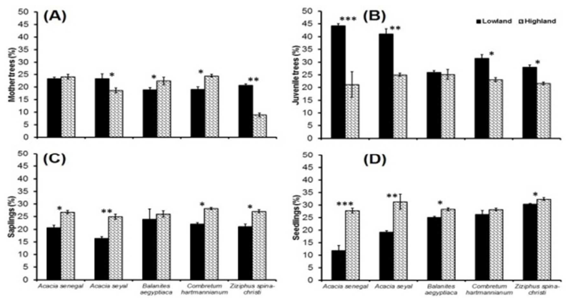

Fig. 5. The proportions (%) of tree development stages of the five top common tree species inventoried in the low and highland sites of Fazara natural forest reserve. (A) mother trees, (B) juvenile trees, (C) saplings, and (D) seedlings. Asterisks on the bars display the significant differences between the sites based on Tuckey Post Hoc test as * = $P \leq 0.05$, ** = $P \leq 0.01$, and *** = $P \leq 0.001$.

Additionally, the top five common tree species showed a good regeneration status in highland sites with a frequency percent ≥ 60% compared to their fair status in lowland sites (Tables 2 & 3). The tree species of Fabaceae family dominate both sites with percentages of 43% and 62% for high and lowland sites respectively (Tables 2 & 3).

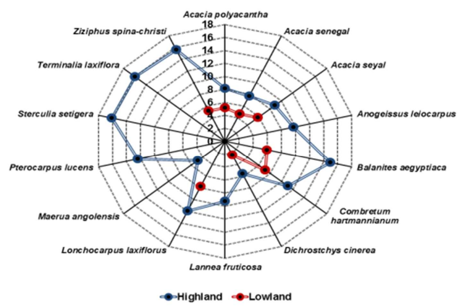

Fig. 6. Mean (±SE) crown width (m) of all tree species inventoried in the low and highland sites of Fazara natural forest reserve.

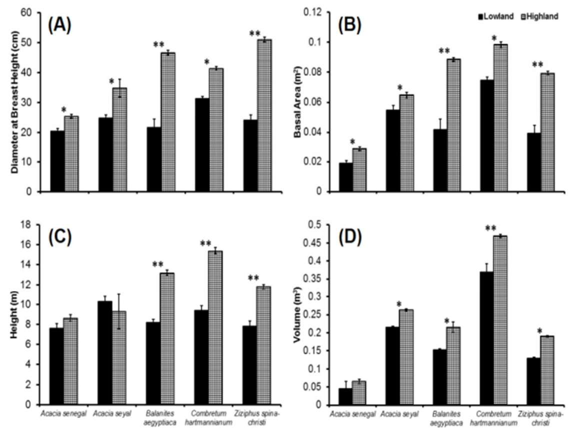

Fig. 7. Mean (±SE) dendrometric parameters of the five top common tree species inventoried in the low and highland sites of Fazara natural forest reserve. (A) diameter at breast height, (B) basal area, (C) height, and (D) volume. Asterisks on the bars display the significant differences between the sites based on Tuckey Post Hoc test as * = $P \leq 0.05$, and ** = $P \leq 0.01$.

Factors driving the changes in species composition and mother tree decline

We found that illegal harvesting is the main contributor to mother tree decline and tree species composition changes. The density of tree stumps and debranched trees at lowland sites were respectively four and three times equal to that of highland sites, with significant differences between sites ($F_{1,72} = 152.3$ and $P < 0.001$; $F_{1,72} = 128.4$ and $P < 0.01$, respectively, Fig. 8). However, the density of debarked trees and root damages were high in highland sites compared to lowland ones ($F_{1,72} = 102.8$ and $P = 0.03$; $F_{1,72} = 112.2$ and $P = 0.04$, respectively, Fig. 8). Moreover, the interviewed participants reported that illegal harvesting, overgrazing, and agricultural activities are the main reasons behind the decline of mother trees within and around the reserve with a frequency of 48%, 24%, and 17%, respectively (Fig. 9).

Table 2. The family, frequency, and regeneration status of tree species inventoried in the highland sites of Fazara natural forest reserve

No	Species	Family	Habit	Frequency (%)	Regeneration status
1	*Acacia polyacantha* Willd.	Fabaceae	Tree	9.6	None
2	*Acacia senegal* (L.) Willd.	Fabaceae	Tree	59.6	Good
3	*Acacia seyal* Del.	Fabaceae	Tree	59.8	Good
4	*Anogeissus leiocarpus* (DC.) Guill . & Perr.	Combretaceae	Tree	11.3	None
5	*Balanites aegyptiaca* (L.) Del.	Balanitaceae	Tree	68.2	Good
6	*Combretum hartmannianum* Schweinf.	Combretaceae	Tree	43.4	Fair
7	*Dichrostachys cinerea* (L.) Wight et Arn.	Fabaceae	Shrub	42.1	Fair
8	*Lannea fruticosa* (Hochst. ex. A. Rich.) Engl.	Anacardiaceae	Tree	16.6	None
9	*Lonchocarpus laxiflorus* (Guill. & Perr.)	Fabaceae	Tree	27.8	Poor
10	*Maerua angolensis* DC.	Capparaceae	Shrub	8.7	None
11	*Pterocarpus lucens* Lepr. ex Guill. et Perr.	Fabaceae	Tree	13.1	None
12	*Sterculia africana* (Lour.) Fiori.	Malvaceae	Tree	26.4	Poor
13	*Terminalia brownii* Fresen.	Combretaceae	Tree	25.2	Poor
14	*Ziziphus spina-christi* (L.) Desf.	Rhamnaceae	Tree	63.1	Good

Table 3. The family, frequency, and regeneration status of tree species inventoried in the lowland sites of Fazara natural forest reserve.

No	Species	Family	Habit	Frequency (%)	Regeneration status
1	*Acacia polyacantha* Willd.	Fabaceae	Tree	28.6	Poor
2	*Acacia senegal* (L.) Willd.	Fabaceae	Tree	51.3	Fair
3	*Acacia seyal* Del.	Fabaceae	Tree	57.6	Fair
4	*Balanites aegyptiaca* (L.) Del.	Balanitaceae	Tree	62.2	Good
5	*Combretum hartmannianum* Schweinf.	Combretaceae	Tree	41.4	Fair
6	*Dichrostachys cinerea* (L.) Wight et Arn.	Fabaceae	Shrub	62.5	Good
7	*Lonchocarpus laxiflorus* (Guill. & Perr.)	Fabaceae	Tree	6.5	None
8	*Ziziphus spina-christi* (L.) Desf.	Rhamnaceae	Tree	46.5	Fair

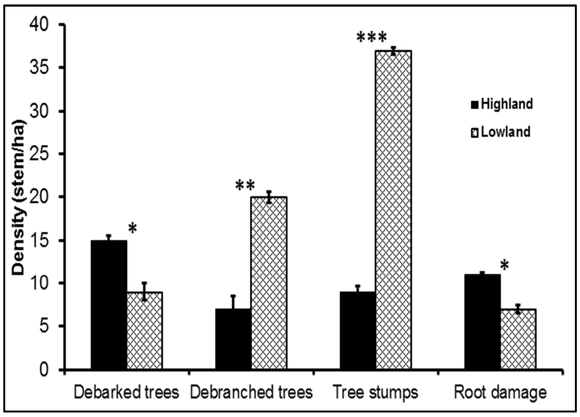

Fig. 8. Mean (±SE) density (stem/ha) of debarked trees, debranched trees, tree stumps, and root damage reported in the high and lowland sites of Fazara natural forest reserve. Asterisks on the bars show the significant differences between the sites based on Tuckey Post Hoc test as * = $P \leq 0.05$, ** = $P \leq 0.01$, and *** = $P \leq 0.001$.

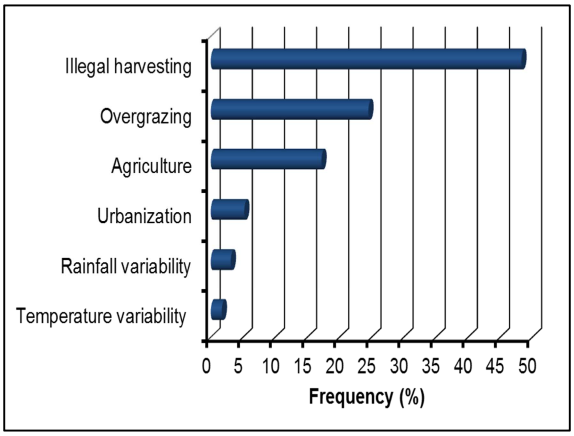

Fig. 9. The six common stated factors driving the changes of species composition and mother trees population decline in Fazara natural forest reserve based on the interviewees responses.

Consequences of mother tree decline

Low species richness and tree density in the lowland sites

The species richness in lowland sites was half of that in highland sites, with a significant difference between sites ($T = 39.4$ and $P < 0.01$, Table 4). While the overall density displayed a low value in the lowland sites ($T = 22.1$ and $P = 0.01$, Table 4), the density of *Acacia seyal* and *Acacia senegal* in the same sites was twice that of highland sites ($F_{1,72} = 75.9$ and $P < 0.001$; $F_{1,72} = 98.3$ and $P = 0.04$, respectively, Fig. 10). However, *Balanites aegyptiaca*, *Combretum hartmannianum*, and *Ziziphus spina-christi* exhibited an inverse pattern (Fig. 10).

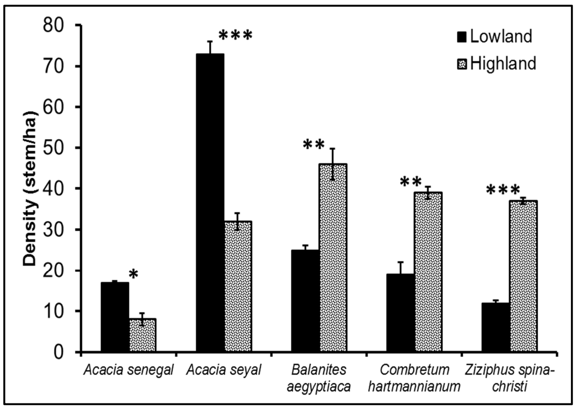

Fig. 10. Mean (±SE) species density per ha for the common top five tree species assessed in the low and highland sites of Fazara natural forest reserve. Asterisks on the bars illustrate significant differences between the stratified sites for each species based on Tuckey Post Hoc test as * = $P \leq 0.05$, ** = $P \leq 0.01$, and *** = $P \leq 0.001$.

Table 4. Species richness and mean tree density (stem/ha) assessed in Fazara natural forest reserve.

Parameter	Highland sites	Lowland sites	*T*	*P*
Species richness	14	8	39.4	< 0.01
Density (stem/ha)	93.2	64.3	22.1	0.01

T = paired-sampled *t*-test, and *P* = probability value

High dominance, frequency, and importance value index (IVI) in lowland sites

Findings show that lowland sites have high values of relative abundance, dominance, frequency, and importance value index (IVI) compared to highland sites (Tables 5 & 6). *Acacia seyal* and *Balanites aegyptiaca* in lowland sites showed the highest values of IVI, which was double that of highland ones (Tables 5 & 6).

Additionally, *Acacia polyacantha* and *Lonchocarpus laxiflorus* tree species displayed the lowest values of relative dominance and abundance throughout the study area, with slight variations across sites (Tables 5 & 6).

Table 5. Species, relative abundance, dominance, frequency and importance value index (IVI) for the inventoried tree species in the highland sites of Fazara natural forest reserve.

No	Species	Family	Relative Abundance	Relative Dominance	Relative Frequency	IVI
1	*Acacia polyacantha*	Fabaceae	1.48	1.84	3.92	7.24
2	*Acacia senegal*	Fabaceae	1.57	2.49	5.88	9.94
3	*Acacia seyal*	Fabaceae	36.11	19.19	12.42	67.72
4	*Anogeissus leiocarpus*	Combretaceae	8.86	7.65	9.8	26.31
5	*Balanites aegyptiaca*	Balanitaceae	16.71	20.24	14.38	51.33
6	*Combretum hartmannianum*	Combretaceae	5.36	10.56	6.54	22.46
7	*Dichrostachys cinerea*	Fabaceae	3.32	3.33	6.54	13.19
8	*Lannea fruticosa*	Anacardiaceae	5.72	1.04	9.15	15.91
9	*Lonchocarpus laxiflorus*	Fabaceae	2.59	3.31	5.88	11.78
10	*Maerua angolensis*	Capparaceae	2.22	9.91	3.92	16.05
11	*Pterocarpus lucens*	Fabaceae	5.17	6.85	2.61	14.63
12	*Sterculia africana*	Malvaceae	3.51	5.25	5.23	13.99
13	*Terminalia brownii*	Combretaceae	4.43	6.23	6.54	17.2
14	*Ziziphus spina-christi*	Rhamnaceae	2.95	2.11	7.19	12.25

Table 6. Species, relative abundance, dominance, frequency and importance value index (IVI) for the inventoried tree species in the highland sites of Fazara natural forest reserve.

No	Species	Family	Relative Abundance	Relative Dominance	Relative Frequency	IVI
1	*Acacia polyacantha*	Fabaceae	2.78	4.25	7.77	14.8
2	*Acacia senegal*	Fabaceae	2.67	3.35	11.65	17.67
3	*Acacia seyal*	Fabaceae	63.23	44.26	25.25	132.74
4	*Balanites aegyptiaca*	Balanitaceae	10.79	24.29	13.59	48.67
5	*Combretum hartmannianum*	Combretaceae	8.58	14.22	11.65	34.45
6	*Dichrostachys cinerea*	Fabaceae	5.45	3.65	12.62	21.72
7	*Lonchocarpus laxiflorus*	Combretaceae	1.05	2.13	3.88	7.06
8	*Ziziphus spina-christi*	Rhamnaceae	5.45	3.85	13.59	22.89

Discussion

Mother trees abundance and adult to juvenile ratio

The study findings of high mother trees, saplings, and seedlings abundance in highland sites compared to lowland ones are consistent with (Gebrehiwot & Hundera, 2014; Hanief *et al.*, 2016; Hassan *et al.*, 2022). Various studies have related the low population of adult and juvenile trees in forests and rangelands to over-utilization (Githae *et al.*, 2011; Maleko *et al.*, 2018; Mohammed *et al.*, 2021), landuse change (Aleza *et al.*, 2018; Alzubair & Hamdan, 2020; Owusu *et al.*, 2021), and management regime changes (Bergeron *et al.*, 2002; Chaudhary *et al.*, 2016; Cheng *et al.*, 2017; Sukhbaatar *et al.*, 2019).

However, for the Fazara case, the low seedlings, saplings, and mother trees abundance in lowland sites can be directly associated with high browsing by livestock and unauthorized logging activities. Literature proved that sites close to human settlements are usually subject to high anthropogenic pressure compared to remote areas (Assogbadjo *et al.*, 2010; Cantarello *et al.*, 2014; Gebeyehu *et al.*, 2019; Mohammed *et al.*, 2021).

Further, the high juveniles of *Acacia senegal* and *Acacia seyal* to other broadleaves tree species reflect the impacts of selective logging practiced by the locals due to their preference of using broadleaved species for timber production rather than Acacias (Mahgoub, 2014; Mohammed *et al.*, 2021). In addition, the invasive nature of *A. senegal* and *A. seyal* (Belsky, 1994; Kingazi *et al.*, 2020; Maua *et al.*, 2020), and their vigorous natural regeneration compared to other tree species like *Balanites aegyptiaca* (Ahmed & Desougi, 2014; Gebru *et al.*, 2019; Hasoba *et al.*, 2020), can potentially contribute to the current regeneration stock.

Though *Ziziphus spina-christi* has a good mother tree abundance in the lowland, it shows a low seedling and sapling abundances resulting from its high palatability by domestic animals (Adam *et al.*, 2013; Beche *et al.*, 2016; Kochare *et al.*, 2018). The observed vertical and horizontal changes in the tree species population of FNFR demonstrate the influences of its neighbor residents and call for urgent interventions to fix such challenges. Besides that, edge sites between the locals settlement and the lowland sites displayed the lowest mother tree abundance due to current anthropogenic pressure, which necessitate an introduction of community forestry concept and an awareness-raising program.

Characteristics of dendrometric parameters and regeneration status

Our results illustrate better dendrometric parameters and regeneration status in highland than lowland sites. Parameters like crown width, total tree height, and basal area are directly associated with soil fertility (Jurgensen *et al.*, 1997; Kosmas *et al.*, 2015; Marone *et al.*, 2017), resources availability (Bindraban *et al.*, 2000; Franklin *et al.*, 2007; Gorgens *et al.*, 2021), biotic and a biotic disturbances (Aubad *et al.*, 2008; Chaturvedi *et al.*, 2012; Lacerda & Kellermann, 2019; Wang *et al.*, 2019), and stage of development (Guzzo *et al.*, 2014; Idrissa *et al.*, 2018; Mohammed *et al.*, 2021). The present of large crowns, DBH, and basal area of mature trees in highland sites of FNFR demonstrate the lower disturbance in these sites compared to lowland ones.

Combretum hartmannianum, a fast-growing broadleaved tree species, dominates the upperstory canopy of both high and lowland sites with a regular crown shape and large basal area. These findings are in line with references (Gebrehiwot & Hundera, 2014; Ibrahim & Osman, 2014; Mohammed *et al.*, 2021). However, the lower basal area of *Acacia senegal*, *Balanites aegyptiaca*, *Lonchocarpus laxiflorus*, and *Ziziphus spina-christi* in lowland sites can directly refer to the intensive harvesting of adult trees for wood utilization and income generation. Researchers (Adekunle & Olagoke, 2011; Mohammed *et al.*, 2021; Piabuo *et al.*, 2021) reported that > 60% of forest tree decline results from illegal harvesting activities and landuse changes.

We also found that the Fabaceae family members dominate the natural regeneration of tree species in FNFR. This family hosts various tree species such as *Acacia seyal*, *Lonchocarpus laxiflorus*, and *Pterocarpus lucens*. The poor regeneration in the lowland sites of FNFR reflects the effects of human activities in this area, particularly livestock rearing and fruit collection. Uncontrolled livestock browsing and fruit collection usually diminish the forest soil seed bank, seed germination, and seedlings recruitment (Carmona *et al.*, 2013; Ewunetu *et al.*, 2021; Mohammed *et al.*, 2021).

Additionally, Unmanaged browsing eliminates the seedling stage and degrades the sapling population (Ball & Tzanopoulos, 2020; Maua *et al.*, 2020; Mohammed *et al.*, 2021). Similar findings were reported in Tanzania (Chakeredza *et al.*, 2007; Ligate *et al.*, 2019), Kenya (Dunne *et al.*, 2011; Lugusa, 2015), Ethiopia (Bayih & Yihune, 2018; Gebeyehu *et al.*, 2019; Tsegu, 2019), Niger (Adekunle & Olagoke, 2011; Idrissa *et al.*, 2018), and India (Samant *et al.*, 2007; Singh *et al.*, 2016).

Factors driving the changes in species composition and mother tree decline

The study results showed that the main driver of change in FNFR is illegal harvesting, which we observed as complete cutting, crown debranching, debarking, and root cutting. Though the Fazara forest accommodates diversified tree species, illegal harvesting can disturb this diversity and affects both adult and juvenile trees. While debranching reduces the tree crown width and seed production (Gaoue & Ticktin, 2008; Mohammed *et al.*, 2021), debarking affects tissue conductivity (Beltrán-Rodríguez *et al.*, 2021; Delvaux *et al.*, 2010; Nieminen *et al.*, 2015), nutrient absorption and uptake (Ihwagi *et al.*, 2012; Sukhbaatar *et al.*, 2019; Zhang *et al.*, 2022), photosynthesis process (Anderson *et al.*, 2006; Naidoo *et al.*, 2010; Nie *et al.*, 2021), and tree growth (Amahowe *et al.*, 2018; Mwakosya &mLigo, 2014; Vieira *et al.*, 2007). A study conducted by (Naidoo *et al.*, 2010) concluded that deep debarking of *Avicennia marina* and *Bruguiera gymnorrhiza* minimized the leaf carbon dioxide exchange and photosynthesis efficiency to < 50%. Moreover, repeated debranching and root harvest can lead to dieback and entire tree death (Marcussi, 2016; Nobre *et al.*, 2016; Pugh, 2018).

The tripartite anthropogenic damages in FNFR resulting from harvesting, grazing, and agricultural practices led to significant variations between high and lowland sites and interrupted their natural dynamics. While light and moderate grazing can enhance woody plants' natural regeneration (Kikoti *et al.*, 2015; Lempesi *et al.*, 2017; Mohammed *et al.*, 2021), overgrazing deteriorates it to a critical level and compacts the soil (Gebru *et al.*, 2019; Kosmas *et al.*, 2015; Krzic *et al.*, 2006). Moreover, as pastoralists represent a considerable proportion of the resident people around FNFR, the species with sensitive stages of development like *Balanites aegyptiaca*, *Pterocarpus lucens*, and *Lannea fruticosa* may dramatically decline. However, as Abu Gadaf Natural Forest Reserve, Elnour Natural Forest Reserve, and Dinder Biosphere Reserve exhibited similar trends (Ibrahim & Hassan, 2015; Mohammed *et al.*, 2021; Mohammed *et al.*, 2021), an integrated management plan and conservation policy are required to address these challenges and minimize their negative impacts.

Consequences of mother tree decline

The low species richness and density in the lowland sites of FNFR, as a consequence of mother tree decline, is in line with (Degrande *et al.*, 2006; Dunne *et al.*, 2011; Haarmeyer *et al.*, 2013; Kimaro & Lulandala, 2013; Kochare *et al.*, 2018; Nyong *et al.*, 2019), who documented that biotic disturbance, particularly overgrazing and unpermitted harvesting for wood, medicine, fodder, and food production, reduced the species richness, density, and regeneration in Cameroon, Kenya, Burkina Faso, Tanzania, Ethiopia, and Nigeria, respectively. As trees are foundation of the forest (Gorgens *et al.*, 2021; Lindenmayer & Laurance, 2017; Poudel *et al.*, 2019), mother trees are the main pillars of this foundation. While the planned pruning, thinning, and brushing improve the growth and quality of forest trees (Franklin *et al.*, 2007; Gaoue & Ticktin, 2008; Osem *et al.*, 2017), over spacing may pave the way for invasive species. Moreover, as trees sequestrate and store carbon in their tissues (Elevitch *et al.*, 2018; Ibrahim *et al.*, 2018; Neya *et al.*, 2019), a reduction in mother trees can negatively affect this function and potentially contribute to the global warming crisis.

Furthermore, *A. seyal* and *B. aegyptiaca* dominate both high and lowlands sites of FNFR with high dominancy in lowland because of higher logging activities for other tree species and the tolerance of *A. seyal* and *B. aegyptiaca* seedlings and saplings. Though biotic and abiotic stressors affect tree resources partitioning (González-Salazar *et al.*, 2013), availability (Fahmi, 2017; Gorgens *et al.*, 2021), and consumption (Chaturvedi *et al.*, 2012; Gustafsson *et al.*, 2012; Hofhansl *et al.*, 2020), the fluctuations in dominance, frequency, and importance value index of FNFR tree species are due to human stresses that eliminated mother tree populations and disturbed their contribution. In contrast, a high decline in mother trees, as for *A. polyacantha* and *Lonchocarpus laxiflorus* tree species, affected their regeneration, abundance, stocking density, and importance value index. Other researchers reported that reduction in mother tree populations slowed litter decomposition (Erdenebileg *et al.*, 2020; Omar & Muhammad, 2016; Scholten *et al.*, 2017), nitrogen fixation (Treydte *et al.*, 2007; Zeng *et al.*, 2017), and the spatial distribution of juvenile trees at highly disturbed sites of natural forests and free rangelands (Endale *et al.*, 2017; Lindenmayer & Laurance, 2017; Marone *et al.*, 2017). Therefore, (Esquivel *et al.*, 2008; Pfeifer *et al.*, 2012; Wang *et al.*, 2020) revealed that protection and reservation of forest had strong and more direct effects on forest structure than species diversity and dominancy.

Conclusion

The study results demonstrated limited juvenile and adult tree abundances in lowland sites of FNFR due to acute anthropogenic practices within and around the reserve. Likewise, we found high regeneration status, stocking density, species abundance and importance value index in the highland sites, with an excellent performance of the tree species belonging to the Fabaceae family. These findings call for new management policies and paradigms, which achieve greater species protection and sustained forest services. Moreover, to safeguard the essential functions of mother and seed-producing trees in Fazara Natural Forest Reserve, it is necessary to control the factors driving the change in the reserve.

The intensive illegal logging and debranching of large and old trees, as well as overgrazing and browsing by livestock, must be managed through community awareness programs, mobile guards, restoration of degraded sites, and afforestation programs. While the new management policy must aim to reduce the severe human pressure and disturbances, natural disturbances can serve as a silvicultural practice to manage the vertical and horizontal structural heterogeneity at highland sites. We recommend the use of a mixed management paradigm that maximizes biodiversity maintenance, forest ecological functions, sustainable timber production, and yield regulation.

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