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Intensive harvesting menaces trees producing fodder, edible fruit, and gum in Abu Gadaf natural reserved forest, Sudan

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ABSTRACT

Background: This study aimed to assess the influence of intensive harvesting on tree dendrometric parameters, seedling recruitment, and sapling density of identified tree species in Abu Gadaf natural reserved forest, Sudan.

Methods: We used a stratified sampling design for data collection, and the identified tree species were classified into five groups based on the main product utilized locally. Data were collected in 46 sample plots of 1000m^2 systematically distributed across the upper and lower land sites of Abu Gadaf natural reserved forest. Analysis of variance, paired-samples t-test, and regressions in JAMOVI and Minitab were performed for data analysis.

Results: Findings revealed that tree-producing gum and edible fruits have small diameters compared to fodder and building pole-producing ones. Although *Acacia polyacantha* and *Acacia seyal* have larger mean diameter in the lowerland sites, *Sterculia africana* and *Sterculia setigera* displayed the inverse pattern with significant differences between sites ($F_{1, 45}$=102.7 and p<0.01; $F_{1, 45}$=108.3 and p=0.01; $F_{1, 45}$=120.2 and p=0.03, $F_{1, 45}$=111.2 and p=0.02, respectively). Moreover, the mean volume of *Anogeissus leiocarpus, Balanites aegyptiaca, Terminalia brownii,* and *Sclerocarya birrea* in upperland sites was twice, three, and five times equal to that of lowerland ones, respectively.

Conclusion: We concluded that intensive harvesting severely affected fodder, edible fruit, and gum-producing trees in the reserve and reduced their populations. We further recommend an introduction of the Taungya system concept for the restoration of the degraded sites.

KEYWORDS

Agroforestry; Biosphere reserve; Firewood; Forest conservation; Natural regeneration

ARTICLE HISTORY

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Introduction

Trees play significant ecological and socio-economic roles through soil enrichment, food provision, income generation, and carbon sequestration [1,2]. All tree parts, including fruits, leaves, twigs, branches, stems, and roots, are frequently utilized to satisfy innumerable needs and services [3,4]. Tree crown properties such as crown size and shape, leaves phyllotaxy, twigs density, and branches arrangement with other edaphic and growth factors determine tree growth activities [5], fruits and seeds production [6]. They also govern the shading area and shade quality [7], reduction of air pollutants, rain filtering, and running-water speed [8,9], wind-breaking efficiency [10,11], and carbon sink adequacy [12]. Moreover, the total tree height, diameter at breast height, and seedlings density are core components for tree volume calculation [13,14], site quality index [12,15], and regeneration efficiency [16,17], respectively. However, over-utilization can interrupt these functions and limit their roles.

Gum-producing trees like *Acacia polyacantha, Acacia seyal, Acacia senegal, Boswellia papyrifera,* and *Sterculia setigera* received a considerable number of studies related to seedling propagation, tapping techniques, ecological range, and their potential to enhance soil fertility [18-21]. Yet, limited literature is available on how intensive harvesting and over-utilization can affect their population dynamics and sustainability. Similar scenarios are observed for fodder, fruit, and pole-producing trees. The study conducted by Damptey et al. concluded that high fodder production in natural forests is strongly associated with other biomass proxies and beneficial arthropods [22]. However, carbon storage potential, population structure, and stand density can dramatically decline due to human stresses and extreme environmental conditions [13,22-24]. Moreover, Benítez-Badillo et al. documented that land use changes influenced the distribution of wild edible fruits and deteriorated the tropical forests of Veracruz State in Mexico [25]. Therefore, studies dealing with the influence of over-harvesting, shifting cultivation, overgrazing, and mining activities on forest trees contribute significantly to the sustainable management of forest resources [22,26-28].

Over-harvesting trees and other forest products reduce forest biodiversity and accelerate land degradation in many continents, including Africa [29-31]. In the Sahel area, with a high percentage of livestock keeping and agricultural activities, reduction in vegetation cover, soil fertility, species richness, and forest yield is typical [2,32-34]. Such reduction can threaten the livelihoods of rural communities in the Sahel,

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particularly the vulnerable societies in Sudan that principally depend on natural forests. One of these forests is Abu Gadaf natural reserved forest.

Abu Gadaf is a natural reserve found in the Blue Nile region, offering numerous functions and services to more than five thousand families living in four villages surrounding the forest [35-37]. The locals within and around this forest harvest timbers for firewood and charcoal production [38,39], green twigs and leaves for livestock feeding [40,41], bark and roots for traditional medicine [35,42], and fruits for food and income generation [36,43]. While harvesting activities are dramatically increasing, information on how this utilization can affect the tree dendrometric parameters, seedlings recruitment, and saplings development is limited. Aiming to fill this gap, we assessed the influence of intensive harvesting on crown properties, tree height, and seedlings density of identified tree species in Abu Gadaf natural reserved forest, Sudan.

The study compared the tree diameter at breast height (DBH), total tree height, crown width, and tree volume between the upperland sites (Mountainous lands) and lowerland sites (Flatlands). We further assessed the seedling, sapling, and adult tree densities within and across the study sites. Additionally, we set two hypotheses. Firstly, lowerland sites have limited seedling and sapling densities with small crown width in comparison to upperland sites. Secondly, the upperland sites have larger tree DBH, total tree height, and tree volume compared to lowerland ones.

Materials and Methods

Study area

The Abu Gadaf Natural Reserved Forest is located at 11° 25′ 00″ N, 11° 31′ 00″ N, 34° 50′ 00″ E, and 34° 55′ 00″ E (Figure 1), covering an area of 4,413.87 ha [35,44]. The forest hosts useful food and feed tree species such as *Acacia senegal, Anogeissus leiocarpus, Balanites aegyptiaca, Boswellia papyrifera, Combretum hartmannianum, Grewia mollis, Lannea fruticosa, Tamarindus indica, Terminalia brownii,* and *Ziziphus spina-christi* [35,43]. The average monthly rainfall differs from <50mm in winter to >300mm in autumn, with a minimum and maximum temperature of 23 °C and 44 °C, respectively [35,36,43]. Moreover, the reserve topography and soil types are sandy soil in the upperland sites and clay soil in the lowerland sites [13,45]. During the rainy season, some wild animals like *Cercopithecus aethiops, Numida meliagris, Phacochoerus aethiopicus, Redunca redunca,* and *Struthio camelus* move from Dinder Biosphere Reserve to Abu Gadaf forest [45,46].

Data collection

We used the stratified sampling design for data collection. The study area was divided based on the forest topography into upper and lower land sites, where 46 sample plots of 1000m^2 were systematically established across the sites. After determining the plot boundary and identifying the tree species, tree diameter (diameter at breast height), total tree height, bole height, and crown height, were measured using diameter tape, Suunto clinometer, and Spiegel Relaskop, respectively [47,48]. The identified tree species were classified into five groups as gum-producing trees, edible fruit-producing trees, building pole-producing trees, fodder-producing trees, and firewood-producing trees. The classification is based on the main tree product utilized by the local community. The crown diameter was measured as described by Mohammed et al. and Hassan et al. [13,45]. All cruised woody plants (tree species) were distinguished into seedlings (<3cm in stem diameter), saplings (≥ 3cm to <7cm in stem diameter), and adult trees (≥ 7cm in stem diameter) as documented by Mohammed et al., Gebeyehu et al. and Ligate et al. [46,49,50].

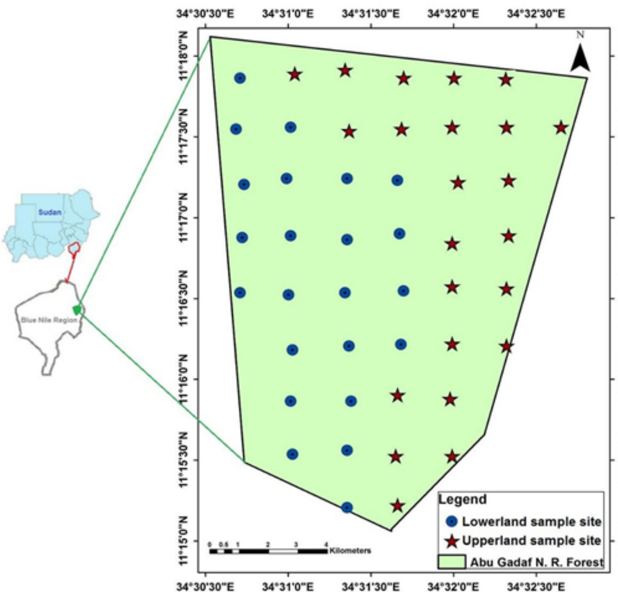

Figure 1. The map of Abu Gadaf Natural Reserved Forest and its stratified upper and lowerland sites.

Data analysis

We checked for normality using the Shapiro test and calculated the tree density and volume using equations 1 and 2 [13,47]. We further compared the crown width, height, and diameter at breast height values of different tree species within the sites and between the upper and lower land sites using a two-way ANOVA in JAMOVI [43,48]. The paired-sample t-test was performed in IBM SPSS to compare the density of seedlings, saplings, and mature trees [14,51]. Tukey post hoc test with a p-value of 0.05 was applied for significant differences as recommended by Gebeyehu et al., Maua et al. and Hasoba et al. [12,17,52]. Moreover, correlations between seedlings density and the No. of tree stumps at the upper and lowerland sites were run in Minitab 17 [53-55].

Tree density= Number of tree stems/area sampled--------- (1)

Tree volume=Tree basal area × total tree height × form factor------------------------ (2)

Results

Tree diameter and height

The trees producing gum and edible fruits have the small diameter at breast height compared to fodder and building pole-producing ones (Figure 2). While *Acacia polyacantha* and *Acacia seyal* illustrated larger mean diameter in the lowerland sites, *Sterculia africana* and *Sterculia setigera* displayed the inverse pattern with significant differences between sites ($F_{1, 45}$=102.7 and p<0.01; $F_{1, 45}$=108.3 and p=0.01; $F_{1, 45}$=120.2 and

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p=0.03, $F_{1, 45}$=111.2 and p=0.02, respectively, Figure 2). Moreover, the mean total height of *Anogeissus leiocarpus, Combretum hartmannianum, Terminalia brownii*, and *Ziziphus spina-christi* in the upperland site was double that of lowerland site with significant differences across sites ($F_{1, 45}$=97.2 and p<0.01; $F_{1, 45}$=101.3 and p=0.01; $F_{1, 45}$=89.8 and p=0.01, $F_{1, 45}$=133.2 and p=0.01, respectively, Figure 3). However, *Acacia senegal* and *Maerua angolensis* showed no significant differences between upper and lowerland sites for both diameter and total tree height (Figures 2 and 3).

Tree crown width and volume

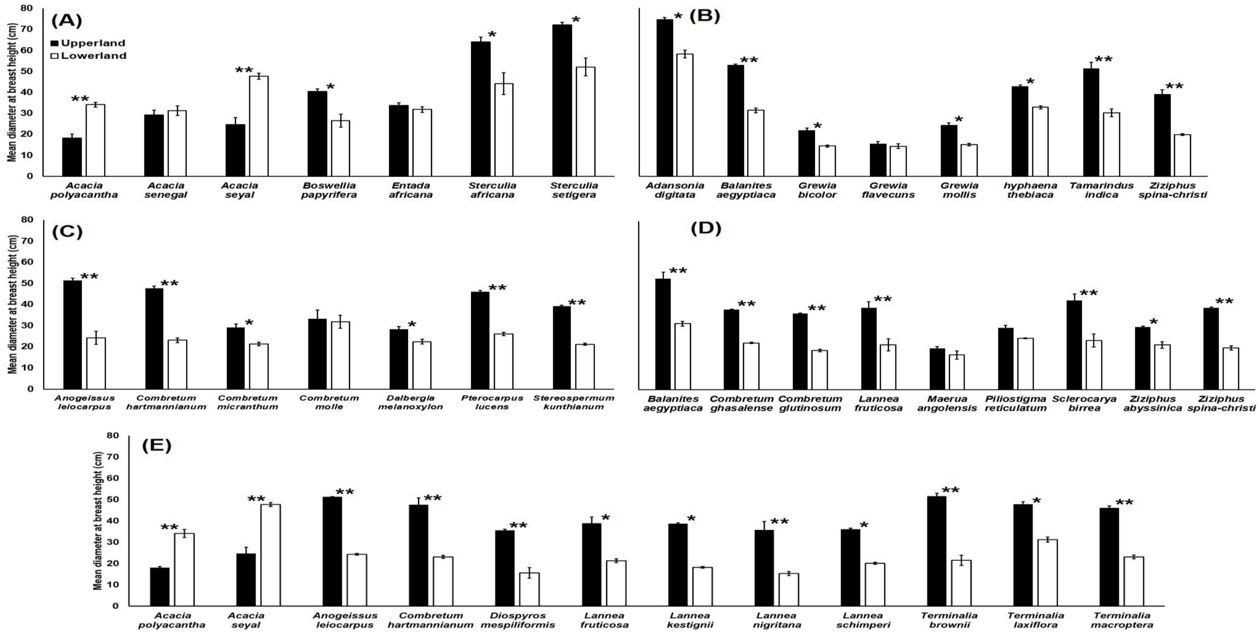

Figure 2. Mean diameter at breast height (cm) for the identified five groups of tree species, classified based on the main utilized product. (A) Gum-producing trees, (B) Edible fruit-producing trees, (C) Building pole-producing trees, (D) Fodder-producing trees, and (E) Firewood-producing trees. Asterisks on the bar illustrate the significant differences between sites for various tree species based on Tukey post hoc test (α =0.05) where *=p<0.05 and **=p<0.01.

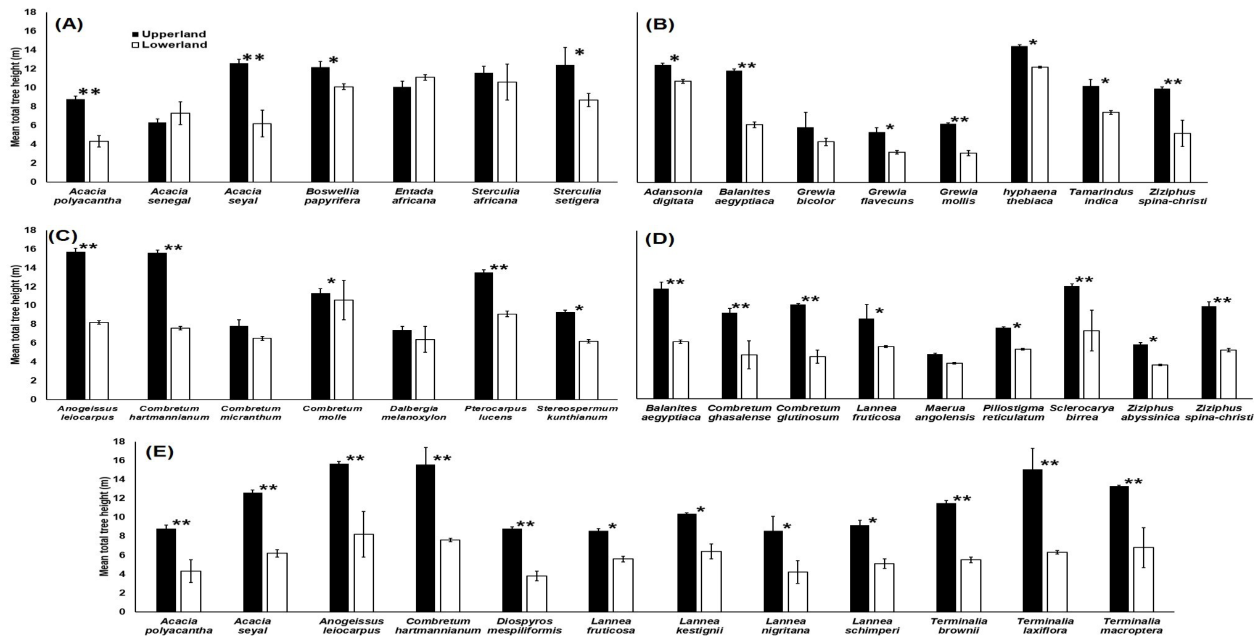

Figure 3. Mean total tree height (m) for the identified five groups of tree species, classified based on the main utilized product. (A) Gum-producing trees, (B) Edible fruit-producing trees, (C) Building pole-producing trees, (D) Fodder-producing trees, and (E) Fire-producing trees. Asterisks on the bar illustrate the significant differences between sites for various tree species based on Tukey post hoc test (α =0.05) where *=p<0.05 and **=p<0.01.

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The mean crown width of Acacia seyal, Combretum ghasalense, and Combretum glutinosum in the upperland site were three times equal to that of the lowerland site and significantly differed between sites (F1, 45=82.3 and p<0.001; F1, 45=128.6 and p=0.01; F1, 45=113.7 and p=0.01, respectively, Figure 4). Though all fodder and firewood-producing trees showed significant differences between sites, Boswellia papyrifera, Combretum micranthum, Combretum molle, Dalbergia melanoxylon, Entada africana, and Sterculia africana exhibited no significant differences across the sites (Figure 4). However, Acacia senegal in comparison to Adansonia digitata and Tamarindus indica displayed an inverse trend with large tree crown in lowerland one (F1, 45=142.3 and p<0.04, Figure 4).

Furthermore, the mean volume of Anogeissus leiocarpus, Balanites aegyptiaca, Terminalia brownii, and Sclerocarya birrea in upperland site were two, three, and five times equal to that of lowerland one, respectively (F1, 45=91.4 and p<0.01; F1, 45=78.6 and p=0.001; F1, 45=73.8 and p=0.001, F1, 45=81.1 and p=0.001, respectively, Figure 5). In addition to that the average volume of Lannea kerstignii and Lannea nigritana in the upperland site, were more than six times to that of lowerland site with significant differences between sites (F1, 45=119.2 and p<0.001; F1, 45=116.1 and p=0.001, respectively, Figure 5). While Acacia polyacantha and Grewia flavescens have the minimum mean volume (<0.09m3), Adansonia digitata and Sterculia setigera attained the maximum mean volume for both lower and upperland sites (>1.4m3 and 2.3m3, respectively, Figure 5).

Based on the group classification, trees producing building poles and firewood had lower mean volume compared to the other three groups (Figure 5). The average volume of Acacia senegal in the upperland site was half of lowerland one with significant differences between sites (F1, 45=79.7 and p<0.03, Figure 5). However, Pterocarpus lucens, Stereospermum kunthianum, Terminalia macroptera, and Ziziphus spina-christi demonstrated an opposite scenario with higher values of mean volume in the upperland site compared to another one (Figure 5).

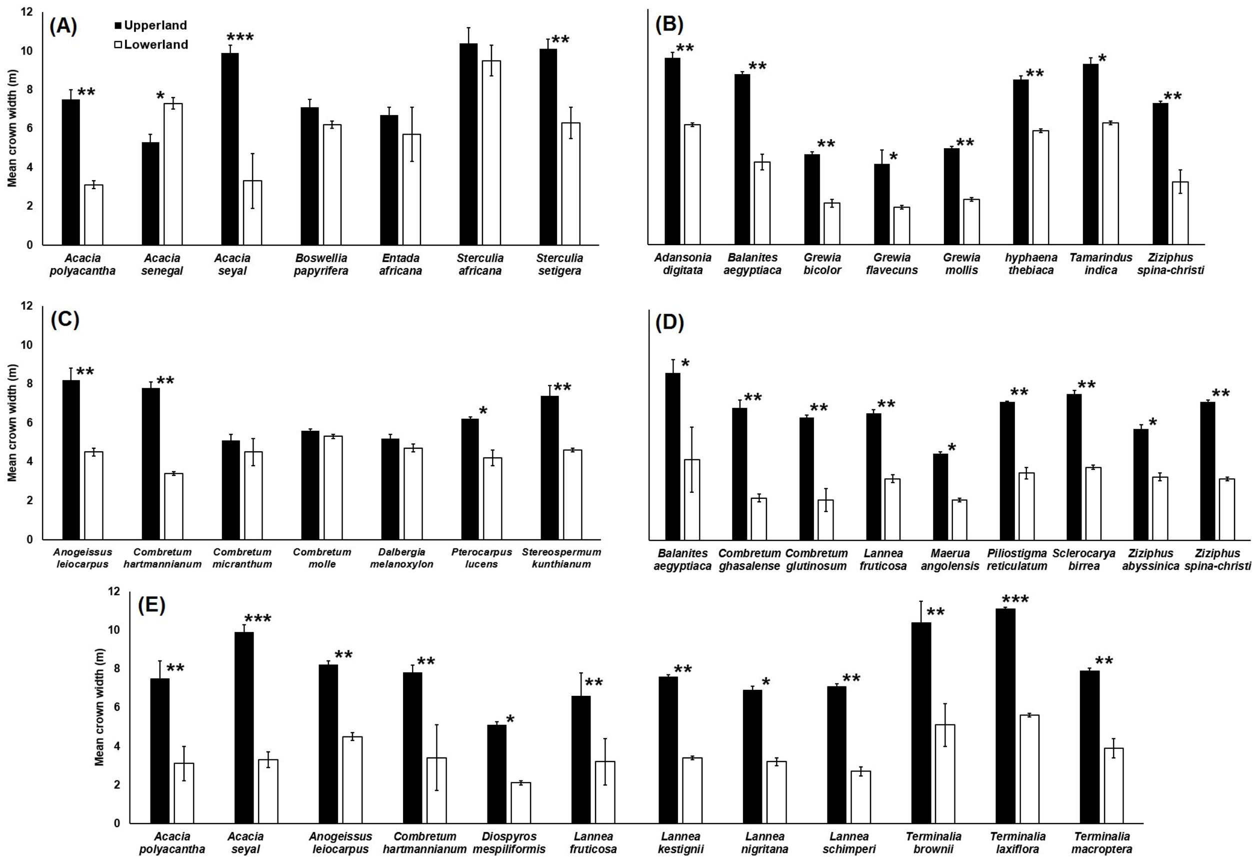

Figure 4. Mean crown width (m) for the identified five groups of tree species, classified based on the main utilized product. (A) Gum-producing trees, (B) Edible fruit-producing trees, (C) Building pole-producing trees, (D) Fodder-producing trees, and (E) Firewood-producing trees. Asterisks on the bar illustrate the significant differences between sites for various tree species based on Tukey post hoc test (α =0.05) where *=p<0.05, **=p<0.01, and ***=p<0.001.

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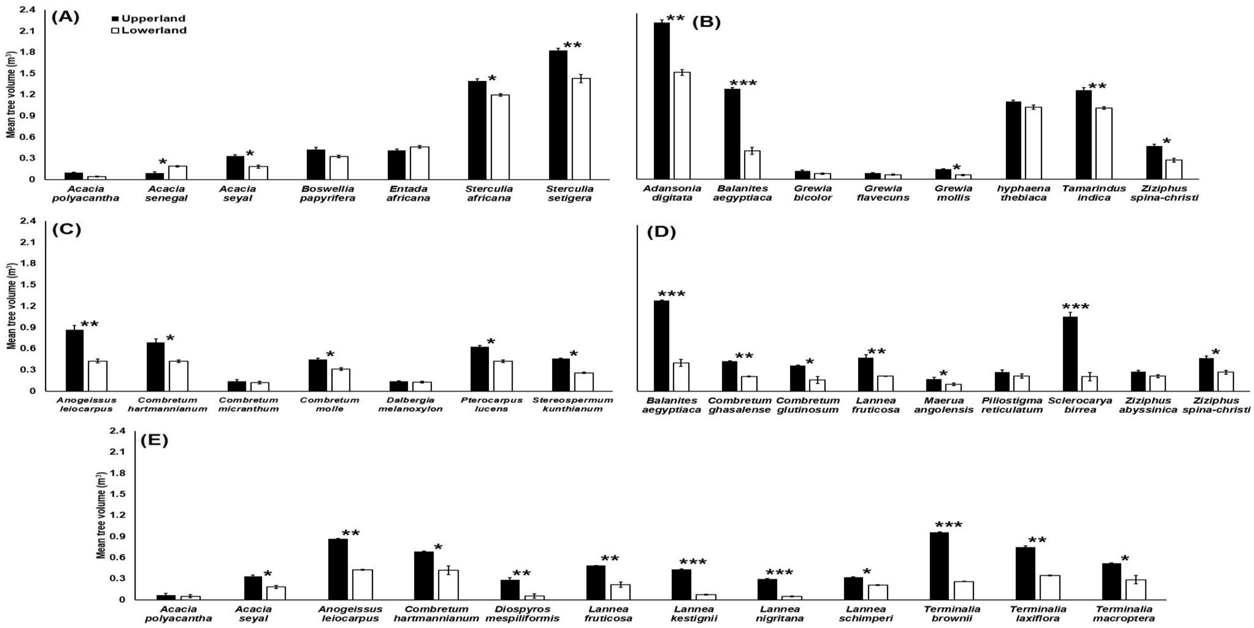

Figure 5. Mean tree volume (m3) for the identified five groups of tree species, classified based on the main utilized product. (A) Gum-producing trees, (B) Edible fruit-producing trees, (C) Building pole-producing trees, (D) Fodder-producing trees, and (E) Firewood-producing trees. Asterisks on the bar illustrate the significant differences between sites for various tree species based on Tukey post hoc test (α =0.05) where *=p<0.05, **=p<0.01, and ***=p<0.001.

Seedlings, saplings, and adult trees density and volume

The correlation between the no. of tree stumps and mean seedlings density of gum-producing, edible fruit-producing, building pole-producing, fodder-producing, and firewood-producing trees in the upperland site demonstrated strong positive relationships with R2=0.99 (β =6.7 and p=0.03; β =5.4 and p=0.04; β =7.4 and p=0.01; β =4.7 and p=0.04; β =7.2 and p=0.01; respectively, Figure 6). However, for lowerland site, it formed an inverse pattern with R2=0.97 (β =1.9 and p=0.01; β =6.8 and p=0.03; β =1.3 and p=0.01; β =11.2 and p=0.04; β =2.6 and P=0.01; respectively, Figure 6). Among the five groups, fodder and firewood-producing trees have the lowest and highest seedlings and saplings densities, respectively (Table 1). The saplings density of firewood-producing trees in the upperland site was two times that of edible fruits, fodder, and firewood producing trees at lowerland site (Table 1). Similar trends were observed for seedlings, saplings, and mature trees volume (Table 1).

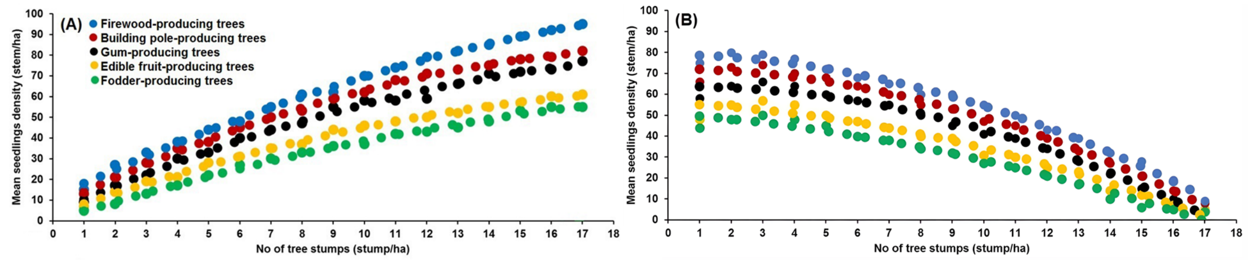

Figure 6. Relationship between the no. of tree stumps (stump ha-1) and seedlings density for gum-producing trees, edible fruit-producing trees, building material-producing trees, fodder-producing trees, and firewood-producing trees in (A) Upperland site and (B) Lowerland site of Abu Gadaf natural reserved forest, Sudan.

Table 1. Mean density (± SD) and volume (± SD) for the identified seedlings, saplings, and mature trees of the five classified groups of tree species inventoried in Abu Gadaf natural reserved forest, Sudan.

Group name	Seedlings			Saplings			Mature trees		
	Upperland	Lowerland	P	Upperland	Lowerland	P	Upperland	Lowerland	P
				Density (stem/ha)					
Gum-producing trees	76 ± 0.4	58 ± 2.6	0.04	72 ± 0.3	51 ± 1.4	0.001	64 ± 0.8	42 ± 2.7	0.03
Edible fruit-producing trees	74 ± 0.6	57 ± 1.9	0.03	63 ± 4.8	41 ± 0.6	0.02	45 ± 1.6	22 ± 0.6	0.001

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Building pole-producing trees	82 ± 3.5	60 ± 0.9	0.001	74 ± 0.5	53 ± 0.7	0.001	52 ± 2.8	33 ± 0.7	0.02
Fodder-producing trees	66 ± 1.3	50 ± 0.7	0.03	65 ± 1.5	43 ± 0.2	0.001	43 ± 0.9	21 ± 1.2	0.001
Firewood-producing trees	85 ± 3.4	58 ± 1.8	0.001	85 ± 5.4	42 ± 0.5	0.001	65 ± 2.9	42 ± 0.9	0.03
Volume (m^3)									
Gum-producing trees	0.811 ± 0.02	0.521 ± 0.01	0.02	0.752 ± 0.02	0.442 ± 0.01	0.01	0.655 ± 0.02	0.546 ± 0.03	0.03
Edible fruit-producing trees	0.789 ± 0.01	0.543 ± 0.01	0.03	0.951 ± 0.02	0.531 ± 0.02	0.02	0.850 ± 0.02	0.562 ± 0.03	0.02
Building pole-producing trees	0.565 ± 0.02	0.311 ± 0.02	0.02	0.498 ± 0.01	0.256 ± 0.02	0.01	0.479 ± 0.03	0.298 ± 0.02	0.01
Fodder-producing trees	0.624 ± 0.01	0.351 ± 0.01	0.01	0.587 ± 0.02	0.321 ± 0.01	0.03	0.543 ± 0.02	0.224 ± 0.03	0.02
Firewood-producing trees	0.721 ± 0.03	0.335 ± 0.02	0.01	0.643 ± 0.01	0.312 ± 0.03	0.01	0.492 ± 0.01	0.215 ± 0.02	0.01

Discussion

Tree diameter and height

We found that trees locally used for the production of building poles and firewood have large DBH in comparison to gum, edible fruits, and fodder-producing trees. Nevertheless, the lowerland site host limited adult and juvenile trees than the upperland one. Similar results were reported by Beche et al., Hassan, Adam et al. and Ereso [20,36,56,57]. The leading species of gum-producing trees are Acacia senegal, Acacia seyal, and Boswellia papyrifera, while for edible-fruit trees, Balanites aegyptiaca, Grewia bicolor, Grewia flavescens, and Grewia mollis are on top. Though Grewia sp. are generally shrubs to small trees, Balanites aegyptiaca and Boswellia papyrifera are sensitive to intensive debarking and debranching, respectively [20,58,59]. Moreover, selective logging of codominant and free-growing trees can eliminate the trees with large diameter and fruit-producing trees [1,27,60]. Researchers, concluded that over-harvesting of mature and dominant trees in the forest and biosphere reserves disturbed the forest stand composition in Ethiopia, Niger, Tanzania, and Kenya, respectively [17,50,61,62].

The findings of total tree height analysis shown that mean height at the lowerland site was half of that in the upperland site for most cruised tree species in Abu Gadaf natural reserved forest [24,28,35]. While Ji et al., Chaudhary et al. and Adekunle and Olagoke referred the low tree height to unauthorized timber harvesting [63-65], Maua et al., Mohammed et al. and Fakhry and Aljedaani related it to both intensive livestock browsing and illegal logging [17,46,66]. The mountainous terrain of the upperland site and its farness from the locals' residences increased the number of mature trees, thus the tree diameter and height. The rough terrain, site accessibility, and utilization purpose can enhance or worsen the species conservation status and population structure [67-69]. However, the current reduction in tree diameter and total height at the lowerland site of Abu Gadaf elucidates the severe effects of illegal logging and debranching applied by the forest- nearby communities that call for quick intervention and restoration programs. Vulnerable tree species like Grewia bicolor, Grewia flavescens and Maerua angolensis need urgent conservation action and detailed study on their spatial distribution and juvenile growth rate.

Though literature documented that, anthropogenic activities like livestock keeping, farming, and charcoal production can negatively affect forest trees [66,70-72], this is the first time to have specific information on gum, fodder, and edible fruit-producing trees, particularly for natural Sudanese forests.

Tree crown width and volume

The study findings revealed that the lowerland site accommodates trees with small crown width and volume compared to the upperland site. The small crown width in Abu Gadaf forest, particularly for fodder-producing trees, can be referred to over-browsing by livestock and frequent removal of fresh twigs and branches for sheep and goat feeding. Studies performed by Hassan et al., Fakhry and Aljedaani and Bondé et al. stated that camel browsing reduced the crown width of fodder trees at highly disturbed sites in Burkina Faso, Saudi Arabia, and Sudan to less than 40%, 60%, and 35%, respectively [45,66,73]. Moreover, Mohammed et al., Ahmed and Desougi, Hassan et al. and Ali et al. reported that illegal cutting of forest trees deteriorated the population of Acacia senegal, Acacia seyal, Combretum hartmannianum, and Terminalia brownii in Tozi, Hegleig, Okalma, and Dinder reserves in Sudan, respectively [13,18,45,74].

Furthermore, the decline in tree volume is directly associated with the reduction in tree height and diameter at breast height which are strongly linked to the site quality, biotic and abiotic disturbances, and other environmental conditions [11,24,33,75]. Intensive harvesting of mother and old-growing

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trees results in limited upper story trees [5,76], lower importance value index [2,15,77], smaller basal area [78,79], and consequently tree volume [13]. Therefore, the limited volume of firewood and pole-producing trees in Abu Gadaf natural reserves forest originates from the current observed illegal logging activity and other anthropogenic deeds like livestock keeping, agriculture, and urbanization. Likewise, outcomes were concluded by Crump et al., Blackham et al. and Ewunetu et al. [80-82].

Seedlings, saplings, and adult trees density and volume

The efficient natural regeneration of forest trees depends on seed viability, suitable edaphic and climatic conditions for seed germination, site competition, and biotic and abiotic disturbances [14,83,84]. Stands with high anthropogenic disturbances, poor soil fertility, and low precipitation rate attain poor seed germination rate, lower seedling growth rate, and consequently limited sapling recruitment [85-87]. Our findings support the previously documented results and highlight the significant influence of human stresses on seedling density and saplings recruitment. The strong positive relationship between the number of tree stumps and seedlings density in the upperland of Abu Gadaf natural reserved forest illustrated that this site is subject to less crown debranching, thus more seed production resulting in more seedlings in the newly opened space. However, for the inverse pattern at the lowerland site, the intensive removal of fruiting branches reduced the number of produced seeds, consequently, seedling and sapling density. Various studies are aligned with these findings [51,88,89].

While browsing commonly affects adult and upper story trees, illegal harvesting impacts mature trees and regeneration [90-92]. This study is among the few that elucidated how intensive harvesting and frequent logging of adult trees can influence the density of seedlings, saplings, and adult trees. The lower density of fodder and edible fruit-producing trees in Abu Gadaf is directly associated with the intensive utilization of these species for food, feed, medicine, and income generation, resulting in a lower density of adult and juvenile trees and demand for a conservation policy and plan. Studies conducted by Aubad et al., Kutnar et al., Tetemke et al. and Wang et al. indicated that combined effects of livestock grazing and logging reduced the species richness, stocking density of adult trees, regeneration ratio, and population structure [93-96]. The species like Adansonia digitata, Balanites aegyptiaca, Hyphaena thebaica, Tamarindus indica, and Ziziphus spina-christi need to be promoted towards the enhancement of local community income and moderation of the increasing pressure on other tree species at the reserve.

Conclusions

We concluded that intensive harvesting by local communities within and around Abu Gadaf natural reserved forest had decreased the population of woody plants, particularly trees producing fodder, edible fruits, and gum. The lowerland site hosts trees with small diameters, crown widths, heights, and volumes compared to the upperland site. Even though Grewia bicolor and Grewia flavescens demand urgent intervention and conservation plan, Adansonia digitata, Balanites aegyptiaca, and Ziziphus spina-christi exhibited a potential source for future afforestation programs and locals livelihoods enhancement. However, more patrolling monitoring in the lowerland site is needed to control the observed human interference and paves the road for the natural restoration of the degraded area. Additionally, an introduction of the Taungya system concept can guide the afforestation programs and rehabilitates the affected sites.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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