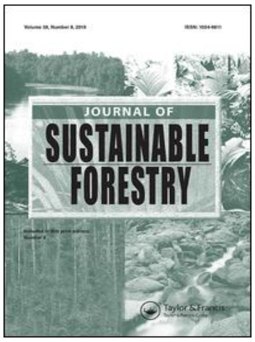

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Livestock Browsing Threatens the Survival of *Balanites aegyptiaca* Seedlings and Saplings in Dinder Biosphere Reserve, Sudan

Elmugheira M. I. Mohammed[a,b], Abbas M. E. Hammed[c], Tamera J. Minnick[d], Patrick A. Ndakidemi[a], and Anna C. Treydte[a,e,f]

[a]Department of Sustainable Agriculture, Biodiversity Conservation and Ecosystem Management, School of Life Sciences and Bioengineering, the Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania; [b]Department of Forest Management Science, Faculty of Forest Sciences and Technology, University of Gezira, Wad Medani, Sudan; [c]Department of Basic Sciences, College of Natural Resources and Environmental Studies, University of Bahri, Khartoum, Sudan; [d]Department of Physical and Environmental Sciences, Colorado Mesa University, Grand Junction, Colorado, USA; [e]Department of Physical Geography, Stockholm University, Stockholm, Sweden; [f]Ecology of Tropical Agricultural Systems, Hans-Ruthenberg Institute, University of Hohenheim, Stuttgart, Germany

ABSTRACT

While the impact of livestock grazing has been frequently assessed for grasses, little is known about how livestock affects tree seedlings and saplings. We explored the effects of goat, cattle and camel browsing on the survival of *Balanites aegyptiaca* seedlings and saplings, a broadleaved evergreen tree species indigenous to Sudan, in Dinder Biosphere Reserve-Sudan (DBR). We used a stratified sampling design with four sites: GOA (mainly browsed by goats), CAT and CAM being mainly browsed by cattle and camels, respectively, while CON was a control area without any livestock browsing. We tested the survival, mortality and recovery of seedlings and saplings across different sites. Our results revealed that mortalities of seedlings in GOA were almost four times higher than that of CAM and CON and twice that of CAT ($F_{3,196}$ = 100.39, P < .001). Further, sapling mortality was three times higher in GOA than that observed in CAT and CON ($F_{3,196}$ = 73.4, P < .001). We found that seedlings recover better than saplings, and, unexpectedly, goat browsing severely affected the natural regeneration of *B. aegyptiaca* in DBR compared to other livestock species. Our study findings contribute to sustainable forest management and show that particularly goat browsing needs to be suppressed for conservation of vulnerable tree species.

KEYWORDS
Herbivory; natural regeneration; protected area; rangelands; woodland

Introduction

Trees play an important ecological role in savanna ecosystems worldwide as they increase the habitat biodiversity, structural complexity and spatial heterogeneity, and they provide food, shelter and shade for animals (Asigbaase et al., 2019; Gebeyehu et al., 2019; Ghanbari et al., 2021; Hasoba et al., 2020; Jevon et al., 2020). Seeds, seedlings, and saplings are the key components for the natural regeneration of many tree species growing in the forests, rangelands, protected areas, and urban, especially the species that rarely regenerate by

CONTACT Elmugheira M. I. Mohammed elmugheira1984@gmail.com Department of Forest Management Science, Faculty of Forest Sciences and Technology, University of Gezira, P.O. Box: 20, Wad Medani, Sudan

coppicing (Blackham et al., 2013; Gómez et al., 2018; Jevon et al., 2020; Suárez-Esteban et al., 2016; Zahawi & Holl, 2009).

A healthy forest population and well-sustained forest ecosystems are usually achievable through the efficient natural regeneration and successful recruitments of seedlings to the sapling stage (Arosa et al., 2017; Cruz et al., 2013; Ritsche et al., 2021; Vayreda et al., 2013). While natural regeneration fosters the resilience of the forest population, enhances its diversity, as well as dynamics (Acácio & Holmgren, 2014; Cruz et al., 2013; Thom & Seidl, 2016), severe abiotic factors like climate change, and uncontrolled anthropogenic activities like overgrazing and intensive browsing by livestock, can disturb this process and interrupts its sustainability (Gebeyehu et al., 2019; Listopad et al., 2018; Mohammed et al., 2021; Reuter et al., 2018).

Overgrazing and intensive browsing are among the principal factors that reduce species diversity and degrade rangelands in different parts of the world (Ball & Tzanopoulos, 2020; Chen & Tang, 2016; Kosmas et al., 2015; Zeng et al., 2017). In arid and semi-arid areas, overgrazing has significantly contributed to a decline in vegetation cover, particularly herbaceous plants (Müller et al., 2014), species richness (Hanief et al., 2016), accelerated soil erosion, and loss of soil organic matter (Zeng et al., 2017).

Moreover, in Africa, and particularly the sub-Saharan countries, intensive grazing and browsing by mammalian herbivores influence the sustainability of various forest types and natural rangelands by reducing their natural regeneration and the tree fruiting branches (Derebe & Girma, 2020; Hawkins, 2017; Kosmas et al., 2015). While Sudan has a considerable number of livestock herds (Mohammed & Hashim, 2015; Wilson, 2018; Yousif & Mohammed, 2012), little is known about their influences on the natural regeneration of forest trees and the recruitment of new seedlings and saplings in their natural forests and rangelands, especially in the Dinder Biosphere Reserve. Few studies have investigated the effects different livestock species have, particularly on the woody vegetation and tree species survival, over time.

Dinder Biosphere Reserve (DBR) is the first and largest biosphere reserve in Sudan, characterized by a diversified plant and animal species, distributed between the transition, buffer, and core zones of the reserve (Hassaballah, 2020; Mahgoub, 2014; Mohammed et al., 2021; Saaid et al., 2019). The reserve encompasses more than 30 tree and shrub species such as *Acacia seyal, Balanites aegyptiaca, Combretum aculeatum*, and *Grewia tenax* (Mohammed et al., 2021; Wassie, 2011); and various wild animals ranging from birds and reptiles to large mammals and carnivores (Mahgoub, 2014; Saaid et al., 2019; Yousif, 2012). Although the biosphere reserve hosts all this biological diversity, the current rapid increase of the human population in and around the reserve could negatively influence these species and reduce their populations. While various studies have addressed the impacts of humans and livestock on herbaceous plants (Hasoba et al., 2020; Hassan & Tag, 2017; Mahgoub, 2014; Pfeifer et al., 2012), studies that investigate the response of woody plants to intensive animal browsing, particularly the tree seedlings and saplings, are rare. One of the highly used tree species, and preferred by the local communities inside the reserve and their neighboring areas, is *B. aegyptiaca*.

Balanites aegyptiaca is a broadleaved and evergreen tree species in the Sahelian region, has various food, medicinal, and agroforestry uses (Tesfaye, 2015) and is widely distributed in Sudan, ranging from sandy soils to clay and heavy clay soils in arid and semi-arid areas (Fadl, 2015). Its fruits are an important source of income for locals, and the tree leaves and young twigs serve as fodder for livestock in agro-silvo-pastoral systems, particularly during the dry season (Elfeel et al., 2007; Fadl, 2015). New shoots and fresh leaves are consumed by humans as vegetables in some parts of Sudan (Tesfaye, 2015), while in Egypt, herbalists use the fruits of *B. aegyptiaca* to treat hyperglycemia, as well as an antioxidant (Abdel-Motaal et al., 2015; Abou-Khalil et al., 2016; Hassanin et al., 2018). The fruits are also high in oil content, which can be used for biodiesel production (Chapagain et al., 2009). Despite its manifold uses, little is known about the vulnerability of *B. aegyptiaca* seedlings and saplings to livestock browsing, and how strongly different livestock species influence their survival and recruitment.

The common livestock species that are generally reared in Sudan for meat and milk production include goat (*Capra hircus*), sheep (*Ovis aries*), cattle (*Bos indicus* and *Bos taurus*), and camel (*Camelus dromedarius*) (Wilson, 2018). These livestock species vary in their dietary preferences based on their digestive system and the seasonal availability of food (Ball & Tzanopoulos, 2020; Larson et al., 2015). Goats are primarily browsers and usually spend over 60% of their feeding period browsing woody perennials and shrubs, while sheep and cattle tend to graze on herbaceous plants and only occasionally browse (Luginbuhl et al., 2010; Sanon et al., 2007). Moreover, camels usually browse the crown of mature trees and shrubs (Ball & Tzanopoulos, 2020). Information on how different livestock species, mainly goats, cattle, and camels, influence the seedlings and saplings of woody species, specifically *B. aegyptiaca*, are lacking. Therefore, this study aims to assess the effects of livestock browsing on the seedlings and saplings of *B. aegyptiaca* in the Dinder Biosphere reserve, Sudan.

We analyzed the influence of goat, cattle, and camel browsing on the survival, diameter, height, and recovery of *B. aegyptiaca* seedlings and saplings within the Dinder Biosphere Reserve, Sudan. Moreover, as goats and camels are mainly browsers and cattle are commonly grazers (Ball & Tzanopoulos, 2020; Luginbuhl et al., 2010; Sanon et al., 2007), we hypothesized that goat and camel browsing more strongly reduces *B. aegyptiaca* seedlings and saplings than cattle. Further, camel commonly browses the crown of mature trees (Ball & Tzanopoulos, 2020) while goats can browse, graze, and debark the stem (Gamoun et al., 2015; Kochare et al., 2018; Lempesi et al., 2017; Poudel et al., 2019). Hence, we assumed that goat browsing will be more harmful to the seedlings and saplings than camel, and the browsed seedlings and saplings will have lower height compared to unbrowsed (healthy) ones.

Additionally, as seedlings are more vulnerable to livestock browsing than already established saplings due to higher biomass of saplings (Hernández & Silva-Pando, 1996; Sanon et al., 2007; Toledo et al., 2011; Zeng et al., 2017), we predicted that the number of recovered seedlings will be lower than that of saplings across all three browsed sites. Our study findings contribute to conservation efforts that aim to protect and manage *B. aegyptiaca* on a sustainable basis. Furthermore, as *B. aegyptiaca* is an iconic tree species in the Sahelian region and a multipurpose tree species across the sub-Saharan countries, our results highlight the vulnerable stages of this species and the livestock species that are most damaging to its seedlings and saplings.

Materials and methods

Study area

The study was conducted in the transition zone of Dinder Biosphere Reserve (DBR), Sudan. The reserve is located at 12°- 26´N, 12°- 42´ N, 34°- 48´E and 35°- 02´E (Figure 1) with a total area of 10,291 km^2 (HCENR, 2004). The average rainfall in the study area ranges from 600 mm to 1000 mm and occurs between May and November, while maximum temperature varies between 30°C and 44°C (Hassaballah et al., 2016; Saaid et al., 2019). The reserve comprises three zones, from the outside to the center: transition, buffer, and core zone, respectively, which show different protection status (Mohammed et al., 2021). Most wildlife including large carnivores are in the core zone, while most human activities are restricted to the transition zone (Ahmed, 2005; Mohammed et al., 2021). The buffer zone

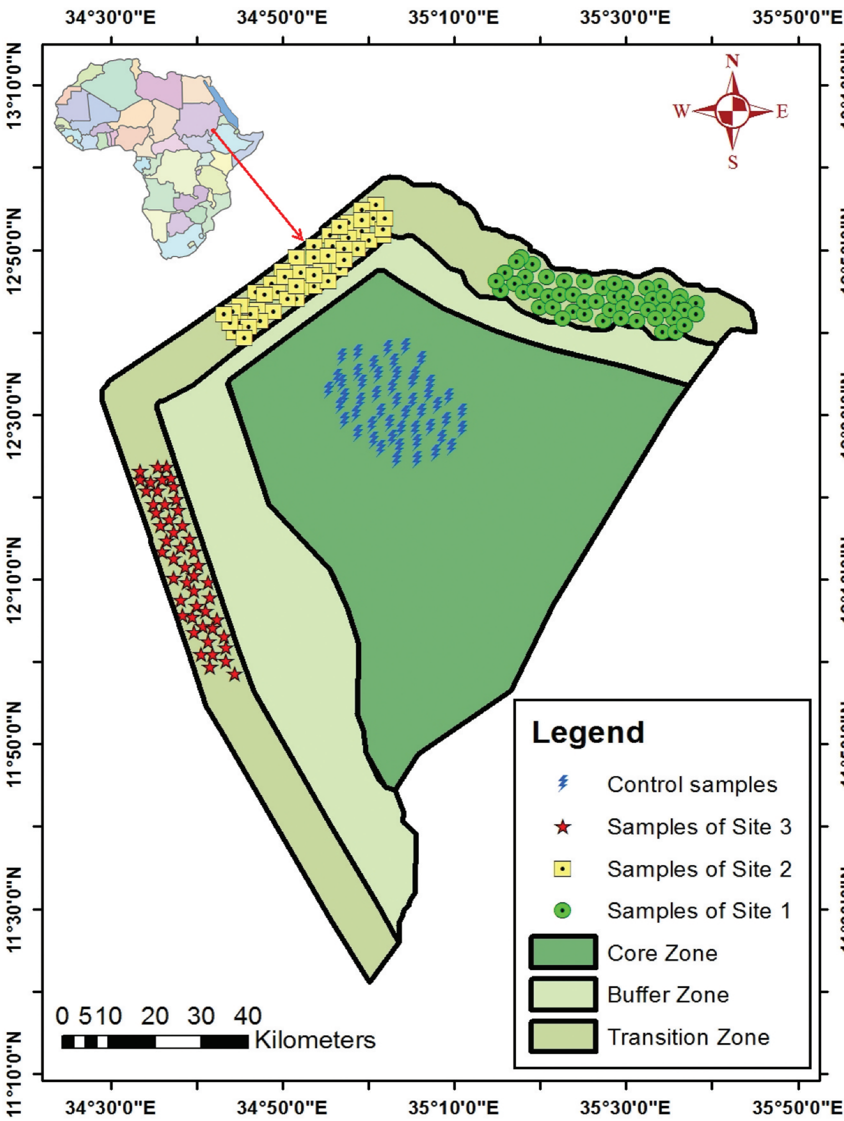

Figure 1. The study area of the Dinder Biosphere Reserve and its three zones. Green circles, yellow squares, pink stars and blue bolts indicate the sample-plots of the four sampled sites, i.e., GOA (site browsed predominantly by goats), CAT (site browsed predominantly by cattle), CAM (site browsed predominantly by camels) and CON (control without livestock browsers), respectively.

acts as a barrier layer between the two extreme zones and hosts a high animal biodiversity with considerable populations of oribi (*Ourebia ourebi*), reedbuck (*Redunca redunca*), warthogs (*Phacochoerus aethiopicus*), ostrich (*Struthio camelus*), Guinea fowl (*Numida meliagris*) and Hussar monkey (*Cercopithecus aethiops*) (Ahmed, 2005; Mahgoub, 2014; Yousif, 2012).

Soils are cracky clay soils in most areas of the reserve except near to Kadalu and Tabya, where some sandy and rocky soils can be found (Mahgoub, 2014; Mohammed & Hashim, 2015). The transition zone hosts more than 20 villages and is under high anthropogenic pressure due to livestock grazing activities and illegal tree felling (Mahgoub, 2014). The common livestock groups in this area are cattle (*Bos indicus and Bos taurus*), goats (*Capra hircus*), sheep (*Ovis aries*) and camels (*Camelus dromedarius*) (Mohammed & Hashim, 2015).

Data collection

We randomly established a total of 200 squared sample plots with an area of 5×5 m^2, which were distributed in four sites as 50 samples per site across the study area (Figure 1). Site 1 (GOA) is mainly browsed by goats, while site 2 (CAT) and site 3 (CAM) are mostly browsed by cattle and camel, respectively. Site 4 (CON) was free of livestock, and we used it as a control site. To determine the dominant and main livestock browser species in each site, we used direct observation of the livestock type, and indirect observations of dung and annual trespassing records for 2018, 2017, 2016, and 2015 (Administration of DBR), as well as the literature (Mahgoub, 2014; Mohammed et al., 2021; Mohammed & Hashim, 2015; Yousif & Mohammed, 2012) (Table 1).

Furthermore, we recorded the number of *B. aegyptiaca* seedlings and saplings in each sample plot, and we classified them into unbrowsed, browsed, or dead across all study sites. Seedlings were defined as young plants with <3 cm in stem diameter (Lopez-Sanchez et al., 2014; Papadopoulos et al., 2017) and usually <1.5 m in height, while saplings were 3 to 7 cm in stem diameter (Kikoti et al., 2015) and up to 2.5 m in height. A seedling or sapling was

Table 1. Livestock species, their numbers and percentages recorded in the Transition Zone of Dinder Biosphere Reserve, Sudan, during the dry season. "Dominant" refers to >50% of the main browser being present in the different category sites. Source: Fieldwork observation of the author (2019– 2020), annual reports of DBR administration (2015–2018) and (Mohammed & Hashim, 2015; Yousif & Mohammed, 2012). GOA = Site browsed predominantly by goats, CAT = Site browsed predominantly by cattle, CAM = Site browsed predominantly by camel, and CON = control without livestock browsers.

Livestock species	Number	Dominant in
Cattle	15,400	CAT
Goat and sheep	15,361	GOA
Camel	4,050	CAM
Donkey	150	CAM

considered to be browsed (affected) if any of its branches or leaves had been damaged by an animal bite (Ahmed, 2005; Kikoti et al., 2015).

For each browsed seedling or sapling, we recorded the number of branches, which had recovered or died from browsing, as well as, the browsing height. Recovery state was based on the presence of fresh leaves and new shoots in seedlings or saplings after being browsed by animals. We also measured the diameter and height of all counted seedlings and saplings by using Vernier caliper and tape. All data were collected during the dry season when livestock was usually found inside the reserve.

Data analysis

Descriptive statistics on dendrometric parameters such as density, diameter, and height were provided using Minitab 17 (Kingazi et al., 2020). Moreover, we used the Shapiro Wilk test in JAMOVI (1.1.7) to check for normality (Missanjo et al., 2015; Truong & Marschner, 2018), paired sampled t-test to compare the mean stem diameter and height of healthy seedlings and saplings versus affected ones within the sites (Mohammed et al., 2021), and Tukey's Post Hoc test at $\alpha = 0.05$ across the browsed sites (Ghosh & Devi, 2019; Truong & Marschner, 2018). Survival, mortality, and recovered seedlings and saplings were also compared across the different browsing categories using the same procedures. Furthermore, to explore the correlation between the recovered seedlings and saplings and their densities in the different browsed sites, we correlated the height of seedlings and saplings with their density using JAMOVI (Version 1.1.7) (Hasnain et al., 2020).

Results

Seedling survival, stem diameter, and total height

We found that the largest seedling stem diameter, and the highest seedling survivals and height were at the control sites (CON) and under camel browsing (CAM) (Figure 2(A), and Table 2). The survivals in CON were three times higher than that in GOA, with a significant difference across the browsed sites ($F_{3,196} = 44.16$, $P < .001$; Figure 2(A)). Moreover, the mortality of seedlings in GOA was almost four times that at CAM and CON, and double that of CAT ($F_{3,196} = 100.39$, $P = .021$; Figure 2(A)).

Additionally, seedling stem diameter varied significantly within the browsed site between the affected and healthy seedlings, particularly under goat browsing ($t = 152.9$, $P = .001$; Table 2). We observed the same trend in the total height of the seedlings ($t = 112.3$, $P = .001$; Table 2). There was a strong negative relationship across the browsed sites between the seedling height and the seedling density, with the highest R^2 value in the CON ($R^2 = 0.81$, $\beta = -6.1$, $P = .034$, Figure 3).

Sapling survival, stem diameter, and total height

In contrast to the seedlings, the survival of *B. aegyptiaca* saplings was only slightly but not significantly different across sites ($F_{3,196} = 2.42$, $P = .067$) albeit there was a trend of lower survival in CAM and GOA compared to CON and CAT (Figure 2(B)). However, sapling

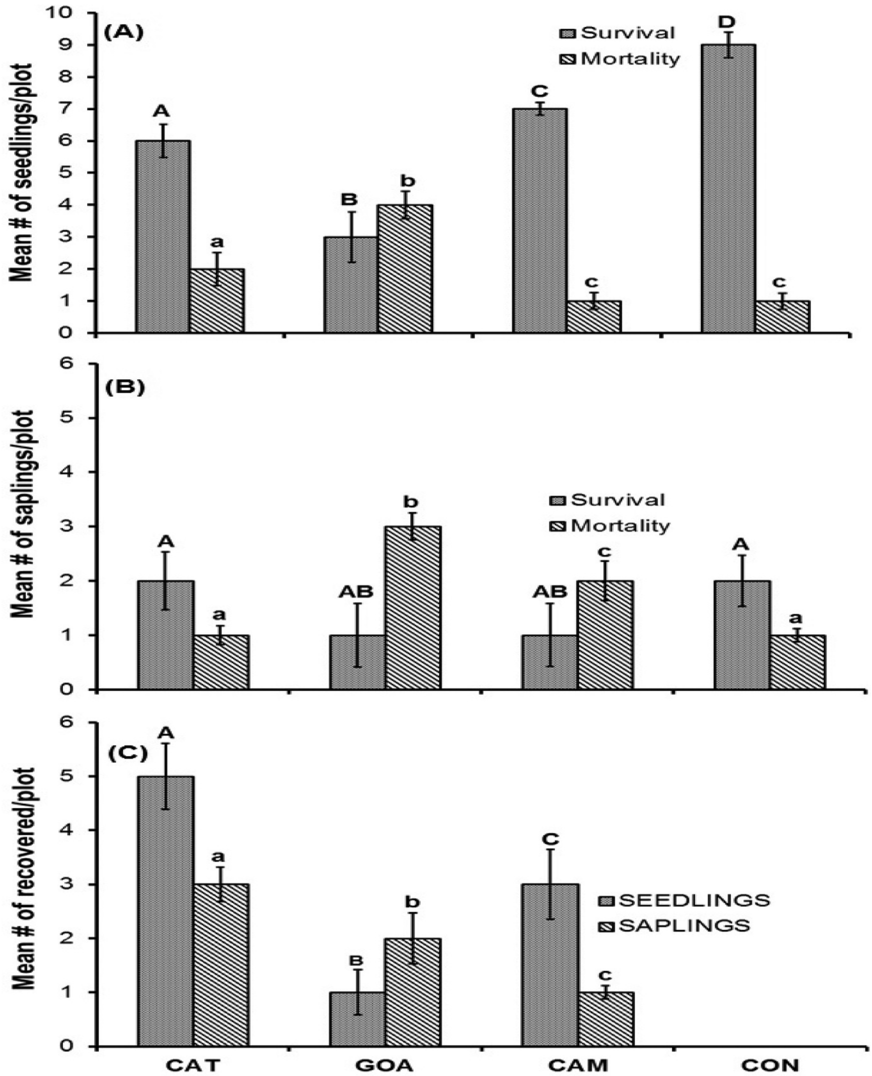

Figure 2. Average (±SE) number of *Balanites aegyptiaca*; (A) seedling survival and mortality, (B) sapling survival and mortality, and (C) recovered seedling and sapling, plotted along the four studied sites with different browsing species where CAT = Site browsed predominantly by cattle, GOA = Site browsed predominantly by goat, CAM = Site browsed predominantly by camel and CON = Control without livestock browsers. Different letters above bars indicate significant differences across the sites according to Tukey's Post-Hoc tests ($P < .05$; n = 1265). Capital letters testing for survival, and small letters for mortality in (A) and (B), while in (C) are testing for seedling and sapling, respectively.

mortality significantly differed across sites ($F_{3,196} = 73.4$, $P < .001$), with mortality in GOA saplings being about three times as high as that of CAT and CON (Figure 2(B)).

We found the largest sapling stem diameter in the CON site, while the highest height was in GOA (Table 3). The diameter of healthy saplings in GOA was double that of affected saplings with a significant difference ($t = 146.2$, $P < .001$, Table 3). Besides that, the height of healthy saplings in the GOA was four times higher than that of affected ones in the same site

Table 2. Average (±SE) stem diameter (cm) and total height (m) of browsed (affected) and unbrowsed (healthy) *Balanites aegyptiaca* seedlings across sites dominated by different browsing species in Dinder Biosphere Reserve, measured over one year. N = total number of seedlings per site, *T* = paired sample *t* test, *P* = probability value. GOA = Site browsed predominantly by goats, CAT = Site browsed predominantly by cattle, CAM = Site browsed predominantly by camel, and CON = control without livestock browsers.

	Healthy		Affected			
Sites	N	Mean (±SE)	N	Mean (±SE)	*T*	*P*
Stem diameter (cm)						
GOA	46	2.0 ± 0.03	114	1.2 ± 0.02	152.9	.001
CAT	208	2.2 ± 0.04	97	1.6 ± 0.03	90.5	.003
CAM	292	2.6 ± 0.02	59	2.1 ± 0.03	132.2	.026
CON	423	2.7 ± 0.01	26	2.3 ± 0.08	94.4	.044
Total height (m)						
GOA	46	1.02 ± 0.09	114	0.32 ± 0.07	112.3	.001
CAT	208	1.15 ± 0.01	97	0.41 ± 0.06	64.7	.001
CAM	292	1.24 ± 0.04	59	0.63 ± 0.08	77.2	.023
CON	423	1.41 ± 0.03	26	0.78 ± 0.02	76.9	.034

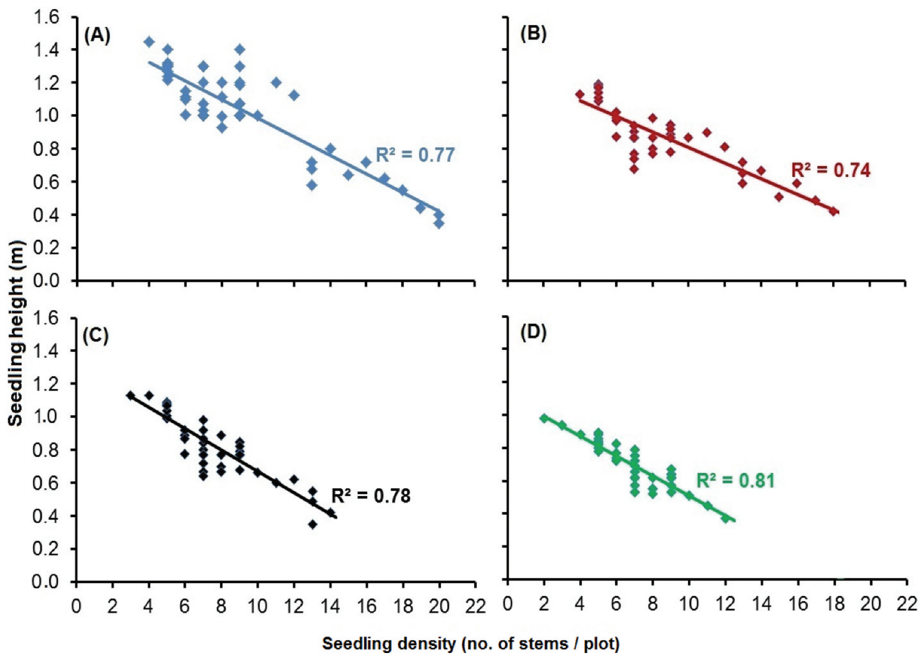

Figure 3. Correlation between the height of *Balanites aegyptiaca* seedlings and the sample plot seedling density in the differently browsed sites of the Dinder Biosphere Reserve, Sudan, assessed over one year. (A) = GOA (Site browsed predominantly by goat), (B) = CAT (Site browsed predominantly by cattle), (C) = CAM (Site browsed predominantly by camel), and (D) = CON (control without livestock browsers); n = 1265.

and twice that in CAT, CAM, and CON ($t = 82.3$, $P < .001$, Table 3). Moreover, our sapling height-density correlation exhibited a strong negative relationship across all browsed sites with the maximum R^2 value in the CAM and CON ($R^2 = 0.86$, $\beta = -13.8$, $P < .001$; $R^2 = 0.86$, $\beta = -14.6$, $P < .001$, Figure 4).

Table 3. Average (±SE) stem diameter (cm) and total height (m) of browsed (affected) and unbrowsed (healthy) *Balanites aegyptiaca* saplings across sites dominated by different browsing species in Dinder Biosphere Reserve, measured over one year. N = total number of seedlings per site, *T* = paired sample *t* test, *P* = probability value. GOA = Site browsed predominantly by goats, CAT = Site browsed predominantly by cattle, CAM = Site browsed predominantly by camel, and CON = control without livestock browsers.

	Healthy		Affected			
Sites	N	Mean (±SE)	N	Mean (±SE)	*T*	*P*
Stem diameter (cm)						
GOA	29	6.3 ± 0.06	72	3.1 ± 0.03	146.2	<.001
CAT	146	6.4 ± 0.02	54	3.8 ± 0.04	235.5	.001
CAM	35	6.6 ± 0.02	66	4.3 ± 0.07	115.7	.021
CON	181	6.7 ± 0.01	19	5.8 ± 0.03	109.6	.032
Total height (m)						
GOA	29	2.32 ± 0.06	72	0.56 ± 0.03	82.3	<.001
CAT	146	1.91 ± 0.02	54	0.84 ± 0.04	67.6	<.001
CAM	35	2.45 ± 0.02	66	1.21 ± 0.07	87.9	<.001
CON	181	1.86 ± 0.01	19	0.92 ± 0.03	85.7	<.001

Seedlings recovered better than saplings in CAT and CAM

The number of recovered seedlings and saplings were significantly different across the browsed sites ($F_{3,196}$ = 17.27, P < .001 and $F_{3,196}$ = 6.76, P < .001, respectively). However, seedlings recovered almost twice as frequently than saplings in CAT and

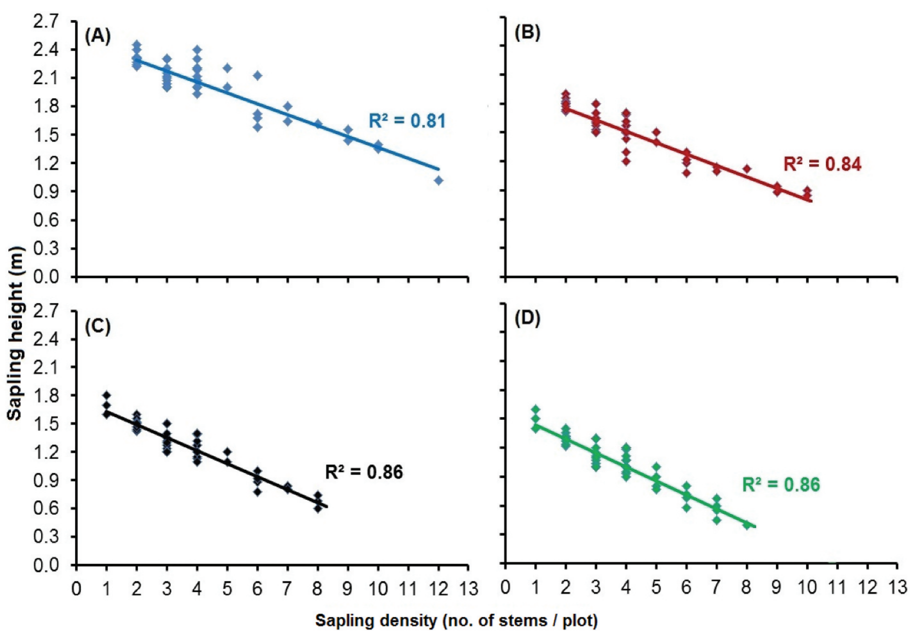

Figure 4. Correlation between the height of *Balanites aegyptiaca* saplings and the sample plot saplings density in the different browsed sites of the Dinder Biosphere Reserve, Sudan, assessed over one year. (A) = GOA (Site browsed predominantly by goat), (B) = CAT (Site browsed predominantly by cattle), (C) = CAM (Site browsed predominantly by camel), and (D) = CON (control without livestock browsers); n = 602.

CAM sites (Figure 2(C)). Fewest recovered seedlings and saplings were observed in GOA and CAM, respectively, while most seedlings recovered in CAT (Figure 2(C)). Recovered seedlings in CAM and CAT were almost three times and double as high than that of saplings in the same sites, respectively (Figure 2(C)).

Discussion

Seedling survival, stem diameter, and total height

Our study results showed that goat browsing is more severe and damaging to the seedlings of *B. aegyptiaca* than cattle and camel browsing. This is in agreement with (Ball & Tzanopoulos, 2020), (Sanon et al., 2007), and (Li et al., 2013) who found that livestock browsing, particularly goats, had negatively affected the seedling survival and seedling recruitment of *Anogeissus dhofarica, Acacia senegal*, and *Caragana intermedia* tree species in Oman, Burkina Faso, and Inner Mongolia, respectively.

Significantly, we found that the stem diameter of browsed seedlings in the GOA site was 40% smaller than unbrowsed ones in the same site and 50% to that in CAT, CAM, and CON. This suggests that goat browsing is more intensive and frequent than cattle and camel, and it might suspend the growth of browsed seedlings or even eliminate them. Our findings are consistent with previous work done by (Maua et al., 2020), who reported that the growth and natural regeneration of 27 native tree species in Kenya had been suspended and limited due to intensive livestock grazing and anthropogenic pressure. Other researchers (Abdou et al., 2016; Assogbadjo et al., 2010; Fakhry et al., 2020; Khamis & Abdalla, 2017) reported similar results on *Prosopis africana, Anogeissus leiocarpus, Cyperus conglomeratus, Ziziphus spina-christi*, and *Grewia tenax*, in Niger, Benin, Saudi Arabia, and Sudan, respectively.

Although the correlation between the seedling's height and their density per plot illustrated a strong negative relationship across all browsed sites, the slopes of their regression lines are different. This could be related to the different responses of *B. aegyptiaca* seedlings to the different browsing and grazing regimes applied by different livestock species. A study conducted by (Lempesi et al., 2017) on *Quercus frainetto* tree species in Greece showed that the intensity of browsing by goats from light to moderate and severe influenced the seedling height and density differently, however, the remained healthy ones grow faster as an advantage of the available space created by the light and moderate browsing. Similar results were reported by (Gebeyehu et al., 2019; Kochare et al., 2018; Negussie et al., 2008) in Ethiopia. Accordingly, light browsing can be used as a biological control to manage the sites with an intensive *B. aegyptiaca* population, but care is needed in the understocked ones.

Sapling survival, stem diameter, and total height

We found that the intensive livestock browsing rigorously affected the saplings of *B. aegyptiaca* and which may subsequently affect its population dynamics. Intensive grazing and browsing over a long period of time lead to population having only mature trees without new recruitment (Ball & Tzanopoulos, 2020; Derebe & Girma, 2020; Kgosikoma et al., 2013), which will eventually lead to the species decline and disappearance. Similar findings were observed in the northern slopes of Mount Kilimanjaro in Tanzania (Kikoti et al., 2015) and Parkland agroforests in western Niger (Idrissa et al., 2018).

Other researchers (Dufour-Dror, 2007; Lopez-Sanchez et al., 2014) reported that the sapling density of *Quercus ithaburensis* and *Quercus agrifolia* in Tabor in Israel and north California, respectively, declined to <50% of the initial population due to intensive browsing and overgrazing of livestock. Further, (Hernández & Silva-Pando, 1996) mentioned that the number of woody species in a Galician oak forest of Northwest Spain declined from 16 to 8 tree species due to intensive browsing. Such a situation is very critical for *B. aegyptiaca*, especially. In our study, the overall sapling survival of *B. aegyptiaca* was <35%, which indicates that the population is at threat, particularly when combined with severe forest fires and climate change. Therefore, we highlight that the new regeneration of *B. aegyptiaca* in the transition zone of the Dinder biosphere reserve must be strongly protected to allow natural recovery.

Furthermore, our study results revealed that the stem diameter of affected saplings in the GOA site was 50% smaller to that of healthy ones, and its height was lower by 70% in the same site and 65%, 50%, and 45% at CAT, CAM, and CON, respectively. This pattern illustrates that *B. aegyptiaca* saplings are very sensitive to livestock browsing, and more attention should be given to tree population conservation, particularly in livestock browsing hotspot areas.

Seedlings recovered better than saplings in CAT and CAM

Our findings illustrate that sites browsed by cattle and camels have higher recovery and survival rates of *B. aegyptiaca* seedlings compared to the site browsed by goats. This may be attributed to the feeding nature of the livestock species; goats generally browse from close to ground level up to a height of 2.10 m (Sanon et al., 2007). In contrast, camels usually browse the crown of mature trees and shrubs rather than young seedlings and saplings (Ball & Tzanopoulos, 2020). Cattle are generally grazers and spend less than 5% of their time browsing on woody plants (Krzic et al., 2006; Sanon et al., 2007). Cattle might, thus, prefer fresh and young seedlings only to saplings, particularly as saplings are more woodier in texture and with a height of >2 m likely out of the cattle browsing height of 1.9 m (Larson et al., 2015; Osem et al., 2017; Lopez-Sanchez et al., 2014).

Lower sapling recovery may result from the reiterative browsing by livestock, specifically by goats. Other researchers (Zamora et al., 2001) have documented that more than 85% of *Pinus sylvestris* saplings in Mediterranean mountains were browsed more than once per season by goats, and more than 30% of their apical shoot have been consumed after establishment. Another study has shown that nomadic grazing had reduced the diversity of medicinal plants, mainly woody species, by 90% in Pakistan and had led to the complete disappearance of two species from overgrazed sites (Sher et al., 2010). This again highlights how fragile the *B. aegyptiaca* population might be, particularly in areas where there is a high expectation of livestock browsing, illegal tree felling, fruit collection, and firewood production.

We documented only low mortalities for both seedlings and saplings of *B. aegyptiaca* in the control site (CON), where livestock was not present. The low mortality might have been caused by other wild grazer and browser species in the area, such as African buffalo (*Syncerus caffer*), reedbuck (*Redunca redunca*), and bushbuck (*Tragelaphus sylvaticus*).

African buffaloes are commonly grazers but can damage the tree seedlings and saplings by trampling on them while grazing other herbaceous species in the site, but also in rare cases, they can browse woody plants (Aremu & Onadeko, 2008; Megaze et al., 2012). Reedbuck are also primarily grazers, with herbaceous plants comprising 80% of their diet, and trees and shrubs 13% and 7%, respectively (Derebe & Girma, 2020). However, their feeding strategy and food preference may depend on the availability of food (Treydte et al., 2006) and season as well (Derebe & Girma, 2020). Bushbucks, on the other hand, are by nature browsers, preferring green leaves and new shoots (Bayih & Yihune, 2018). Hence, we suggest that the slight mortality in CON may mainly result from bushbuck browsing rather than from African buffalo and reedbuck.

Conclusion

Our study has established that livestock browsing is a major constraint and hindrance for natural tree regeneration in Dinder Biosphere Reserve (DBR), particularly for vulnerable woody species such as *Balanites aegyptiaca*. Our results revealed that exposure of *B. aegyptiaca* seedlings and saplings to livestock browsing, especially goats, strongly affects this species' natural regeneration and eliminates the seedling recruitment. We also demonstrated that seedlings recover better than saplings under cattle and camel browsing, while saplings showed less strong responses. Goat browsing eliminated >60% of *B. aegyptiaca* seedlings in GOA compared to the control (90% of seedling survival). Furthermore, as *B. aegyptiaca* is also highly used by the local communities, especially the fruits, we expect a decline in this species' population if no further measures are taken. We claim that once the species reaches the sapling stage, it is no longer palatable/preferable by cattle, and in such areas, cattle grazing can be allowed. We recommended a monitoring program to regulate and control the browsing of livestock species in DBR to ensure the natural regeneration of *B. aegyptiaca* and to restore the affected areas. Our study outcomes contribute potentially to sustainable forestry and are highly valuable for managing similar systems at regional and global levels.

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Declaration of interest statement

The authors declare no conflict of interest.

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