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Effects of livestock browsing and illegal harvesting on natural regeneration and ecology of balanites aegyptiaca in dinder biosphere reserve, Sudan

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EFFECTS OF LIVESTOCK BROWSING AND ILLEGAL HARVESTING ON NATURAL REGENERATION AND ECOLOGY OF *Balanites aegyptiaca* IN DINDER BIOSPHERE RESERVE, SUDAN

Elmugheira Mockarram Ibrahim Mohammed

A Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy in Life Sciences of the Nelson Mandela African Institution of Science and Technology

Arusha, Tanzania

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ABSTRACT

Livestock browsing, and illegal harvesting often influence natural woodlands, rangelands, and biosphere reserves. However, the resulting tree species diversity, composition, and population structure have rarely been quantified. This study explored the status of tree diversity, composition, and the growth of *Balanites aegyptiaca*, across 100 sample plots of 25 m x 40 m at disturbed and non-disturbed sites in Dinder Biosphere Reserve, Sudan (DBR). The dendrometric parameters of *B. aegyptiaca*, fruit production, and the soil-chemical properties were also assessed in the same sample plots. Moreover, to examine the response of *B. aegyptiaca* seedlings and saplings to livestock browsing, the study used a stratified sampling design with four sites been browsed by goats, cattle, camels, and control, respectively. The study data was collected over two years from January 2019 to January 2021. It was observed that non-disturbed sites had double tree diversity than that of disturbed ones ($T = 32.6$, $p < 0.001$), and their seedlings and saplings constituted more than 70% of the entire population ($F_{2,48} = 116.4$, $p = 0.034$; $F_{2,48} = 163.2$, $p = 0.021$, respectively). The soil nitrogen and phosphorus contents beneath trees in non-disturbed sites were almost double that of those in the disturbed site ($F_{1, 196} = 68.1$, $p < 0.001$; $F_{1, 196} = 97.9$, $p < 0.001$, respectively) while sodium and electrical conductivity were by about 50% lower ($F_{1, 196} = 535.8$, $p < 0.001$; $F_{1, 196} = 16.1$, $p < 0.001$, respectively). Mortalities of seedlings under goat browsing were four times higher than that under camel browsing and control and twice as high than under cattle browsing ($F_{3,196} = 100.39$, $p < 0.001$). Sapling mortality was three times higher under goat browsing compared to cattle and control ($F_{3,196} = 73.4$, $p < 0.001$). The study found that seedlings recover better than saplings, and, unexpectedly, goat browsing severely affected the natural regeneration of *B. aegyptiaca* in DBR. Illegal harvesting in DBR severely reduced tree structure and recruitment parameters of *B. aegyptiaca*, which might also impact soil fertility. Intensive monitoring and awareness-raising programs are urgently needed to conserve this vulnerable tree species.

DECLARATION

I, Elmugheira Mockarram Ibrahim Mohammed, do hereby declare to the Senate of the Nelson Mandela African Institution of Science and Technology that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for degree award in any other institution.

Elmugheira Mockarram Ibrahim Mohammed		
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Prof. Anna Treydte		26. 11. 2021
Supervisor 1	Signature	Date
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CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the Nelson Mandela African Institution of Science and Technology a dissertation titled "*Effects of livestock browsing and illegal harvesting on natural regeneration and ecology of Balanites aegyptiaca in Dinder Biosphere Reserve, Sudan*" for partial fulfillment of the requirements for the degree of Doctor of Philosophy in Life Sciences at the Nelson Mandela African Institution of Science and Technology.

Prof. Anna Treydte		26. 11. 2021
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DEDICATION

I dedicate this work to my wife Ms. Mulhima Babiker Ali, and my two daughters, Ms. Jumanah Elmugheira Mockarram Ibrahim and Ms. Janat Elnugheira Mockarram Ibrahim. Dear lovely family, please accept my apologies for being far from you for all these years, it will be ending soon.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Species Abundance
BR	Biosphere Reserve
CABI	Centre for Agriculture and Bioscience International
CAM	Study sites that mainly browsed by camels
CAT	Study sites that mainly browsed by cattle
CD	Core Diameter
CH	Crown Height
C/N	Carbon to Nitrogen Ratio
CON	Study sites that been left without livestock
CW	Crown Width
D	Species Dominance
DBH	Diameter at Breast Height
DBR	Dinder Biosphere Reserve
ECe	Electrical Conductivity
F	Species Frequency
FAO	Food and Agriculture Organization
GOA	Study sites that mainly browsed by goats
H	Total Tree Height
HCA	Hierarchical Cluster Analysis
HCENR	Higher Council for Environment and Natural Resources
IB	Blackman index
IFAD	International Fund for Agricultural Development
IVI	Importance Value Index
K	Potassium
N	Nitrogen
Na	Sodium
NTFPs	Non-timber Forest Products
PA	Protected Area
PCA	Principal Component Analysis
P	Phosphorus
RA	Relative Abundance
RD	Relative Dominance

RF	Relative Frequency
SOC	Soil Organic Carbon

CHAPTER ONE

INTRODUCTION

1.1 Background of the Problem

Trees and shrubs play indispensable ecological functions in savanna ecosystems globally as they promote habitat biodiversity, population complexity, climate resilience, and stand heterogeneity, and they usually support various animal species by giving feed, shelter, shade, and nests (Assogbadjo *et al*., 2010; Fakhry *et al*., 2020; Ghanbari *et al*., 2021; Hofhansl *et al*., 2020; John *et al*., 2020; Mohammed *et al*., 2021). On the other hand, forests, plantations, biosphere reserves (BRs), and other protected areas (PAs) as worldwide known as sites of diversified trees, shrubs, herbaceous plants, and animal species have always supported human lives through the provision of food, wood, and non-wood products, medicine, recreation sites, and shelter (Asigbaase *et al*., 2019; Maua *et al*., 2020; Mukul *et al*., 2016; Powell *et al*., 2013; Treydte *et al*., 2007). However, management of these resources sustainability is a fundamental element towards the satisfaction of current and future generation needs.

The dramatic worldwide increase in human populations creates more demands for resources and hinders the biological diversity of both fauna and flora in both protected and unprotected areas (Cantarello *et al*., 2014; Cheng *et al*., 2017; Hasoba *et al*., 2020; Ouédraogo *et al*., 2019). Moreover, anthropogenic activities such as intensive livestock grazing and browsing, illegal harvesting of trees and tree products, agricultural expansion and land-use change, and overexploitation are among the common factors that disturb the tree species population dynamic and suppress their natural regeneration (Mohammed *et al*., 2021; Piabuo *et al*., 2021; Sales-Baptista *et al*., 2016; Wang *et al*., 2019). Therefore, understanding the effects of these factors on both adult and young trees can guide the restoration of degraded areas and lead to better protection and management of well-established ones.

In Africa, particularly Sub-Saharan countries and the Sahel region, overgrazing and illegal harvesting had led to serious ecological challenges vary from habitat destruction and fragmentation, soil compaction and deterioration to deforestation, desertification, and tree species disappearance (Assogbadjo *et al*., 2010; Nacoulma *et al*., 2016; Ouédraogo *et al*., 2019; Sanon *et al*., 2007). While cutting of tree branches to feed livestock, stem debarking for medicine, and logging of the whole tree for timber uses damage adult trees, browsing, on the other hand, are affecting young seedlings and saplings (Derebe & Girma, 2020; Lopez-Sanchez *et al*., 2014;

Negussie *et al*., 2008; Piabuo *et al*., 2021; Sukhbaatar *et al*., 2019). Accordingly, information on the species composition and population structure is of high significance, especially for a country like Sudan, where rangelands and protected areas are under increasing anthropogenic pressure, in particular, after the separation of South Sudan.

Recent studies carried out in Sudan by Hasoba *et al*. (2020), Mohammed *et al*. (2021), and Younis *et al*. (2018) showed that the tree species richness, stocking density, and the stand composition in different natural forests are declining. However, information on how tree seedlings, saplings, and seed-producing trees had been affected by livestock browsing and illegal harvesting are scarce.

Tree seeds, seedlings, and saplings are the core constituents of the natural regeneration for various tree species, especially the species that rarely regenerate by coppicing (Ghanbari *et al*., 2021; Hammond *et al*., 2021; Lacerda & Kellermann, 2019; Negussie *et al*., 2008). Sufficient and effective natural regeneration of a tree species improves their population resilience, diversity, productivity, and sustainability (Arosa *et al*., 2017; Endale *et al*., 2017; Singh *et al*., 2016; Storch *et al*., 2018). Therefore, well-sustained natural regeneration can foster the recruitment of tree seedlings to saplings and maintain a healthy population with all stages of development.

Tree species like *Balanites aegyptiaca* are highly used in different regions in Sudan as food and fodder with several medicinal applications (Elfeel & Warrag, 2011). However, the available knowledge on how this species' population responds to livestock browsing and illegal harvesting activities is limited. Thus, there is an urgent need to bridge this gap and reveal an up-date and viable data that can guide the sustainable management and conservation of the species in Sudan.

1.2 Statement of the Problem

Various studies had addressed the effects of anthropogenic pressure on forest reserves, rangelands, and unprotected areas populations (Aubad *et al*., 2008; Fakhry *et al*., 2020; Gebeyehu *et al*., 2019; Kimaro & Lulandala, 2013; Kutnar *et al*., 2019; Neelo *et al*., 2015). However, information on how biosphere reserves have been affected by such pressure is still limited and needs to be explored.

Biosphere reserves (BRs) host considerable biodiversity and play a core function towards the fulfillment of the daily local community needs as well as different ecological roles at regional and global levels (Ghanbari *et al*., 2021; John *et al*., 2020; Kim & Eltahir, 2004; Pfeifer *et al*., 2012; Reuter *et al*., 2018). These roles are important in Sudan, particularly in marginalized areas, remote sites, and forest-based villages (Elmekki, 2008; Mahgoub, 2014; Wassie, 2011). One of the most famous BR in Sudan is Dinder Biosphere Reserve (DBR). However, information on how the increasing livestock grazing, browsing, and illegal harvesting affects this reserve is limited.

Dinder Biosphere Reserve (DBR) is the oldest and first biosphere reserve in Sudan (Mahgoub, 2014; Mohammed *et al*., 2021). It hosts more than thirty-three tree and shrub species and different animal species, vary from small reptiles, birds, and mammals, to carnivores and aquatic animals (Hassaballah, 2020; Mohammed & Hashim, 2015; Mohammed *et al*., 2021; Saaid *et al*., 2019; Yousif, 2012). The common tree species in the reserve include *Acacia seyal*, *Acacia senegal*, *Acacia mellifera*, *B. aegyptiaca*, *Combretum hartmannianum*, *Lannea fruticosa*, and *Ziziphus spina-christi* (Ahmed, 2005; Hassaballah *et al*., 2016; Mohammed *et al*., 2021; Yousif & Mohammed, 2012). While, the frequently observed wild animals are African buffalo (*Syncerus caffer*), warthogs (*Phacochoerus aethiopicus*), baboon (*Papio anubis*), reedbuck (*Redunca redunca*), and ostrich (*Struthio camelus*). Moreover, *B. aegyptiaca* is widely utilized by locals for food and feed as well as medicine. Its fruits are edible, and new shoots and fresh leaves have usually been used to made salads, while the roots, bark, and heartwood have frequently been used in traditional medicine (Abou-Khalil *et al*., 2016; Adam *et al*., 2013; Hassanin *et al*., 2018; Idrissa *et al*., 2018; Okia, 2013).

Despite the various uses of *B. aegyptiaca*, little had been reported about its population and how intensive livestock browsing has disturbed the species growth, dynamic, and population structure. Additionally, data on the consequences of increasing illegal harvesting of the tree crown branches on fruit production, seedling recruitment, and saplings distribution are rare. Therefore, there is a high demand to explore the effects of livestock browsing and illegal harvesting on the natural regeneration and population structure of *B. aegyptiaca* in DBR and how the possible decline of the species can affect the local community income.

1.3 Rationale of the Study

Although *B. aegyptiaca* products are highly consumed and sold in different African countries (Beche *et al*., 2016; Elbadawi *et al*., 2017; Idrissa *et al*., 2018; Okia, 2013; Ouédraogo *et al*., 2019), the available information on the status of its natural regeneration and population structure is scarce. In Sudan, up-to-date data on the stocking density, growth status, population composition, adult to juvenile ratio, and natural regeneration of *B. aegyptiaca* across the country and in the protected areas, in particular, are lacking (Elfeel *et al*., 2007; Food and Agriculture

Organization [FAO], 2015; International Fund for Agricultural Development [IFAD], 2012; Osman & Idris, 2012). Recently released documents (Adam *et al*., 2013; Fahmi, 2017; Hasoba *et al*., 2020; Mohammed *et al*., 2021) necessitated the significance of exploring the status of the natural regeneration of *B. aegyptiaca* tree species in natural and protected areas in Sudan towards its conservation and restoration in degraded sites.

While evidence of the effects of overgrazing on herbaceous and perennial plant density (Fraser *et al*., 2001; Kutnar *et al*., 2019; Ssegawa & Kasenene, 2007), composition (Gebrehiwot & Hundera, 2014; Rahman *et al*., 2016), and diversity (Osem *et al*., 2017; Treydte *et al*., 2009; Treydte *et al*., 2007) is quite available, there is a knowledge gap in the impacts of mammalian herbivory on woody species, especially *B. aegyptiaca*. Information on how intensive browsing and illegal harvesting affect the recruitment of *B. aegyptiaca* seedlings, fruit production, and dendrometric characteristics are limited. Therefore, this study explored the effects of livestock browsing and illegal harvesting on the natural regeneration of *B. aegyptiaca* in the DBR. It also analyzed the effects of browsing and illegal harvesting on the chemical properties of the DBR soil. Further, the study investigated the effects of the possible decline of the *B. aegyptiaca* population on the income and livelihood of the local community within and around the Reserve.

1.4 Research Objectives

1.4.1 General Objective

The main objective of this study was to assess the effects of livestock browsing and illegal harvesting activities on the distribution and natural regeneration of *B. aegyptiaca* in DBR, Sudan.

1.4.2 Specific Objectives

(i) To explore the effects of livestock browsing and illegal felling on the tree species diversity and composition in DBR and growth of *B. aegyptiaca* in DBR.

(ii) To identify the sensitive stage (seedling or sapling) at which *B. aegyptiaca* is most strongly affected by livestock browsing.

(iii) To assess the effect of illegal cutting of *B. aegyptiaca* branches on tree survival, fruit production, and seedling recruitment.

(iv) To quantify differences in the soil chemical properties beneath the affected (browsed/harvested) and healthy (unbrowsed/unharvested) trees in the disturbed and non-disturbed sites.

(v) To evaluate the influence of *B. aegyptiaca* population decline on the income of local people.

1.5 Research Questions

(i) How strongly do livestock browsing and illegal felling affect the tree species diversity and composition in DBR and growth of *B. aegyptiaca*?

(ii) At which stage is *B. aegyptiaca* mostly affected by livestock browsing in DBR?

(iii) To what extent does illegal cutting of *B. aegyptiaca* branches affect tree survival, fruit production, and seedling recruitment in DBR?

(iv) To what extent do the chemical properties of the DBR soil vary beneath the affected and healthy trees in the disturbed and non-disturbed sites?

(v) How does the decline of natural regeneration and stock of *B. aegyptiaca* affect the income of local communities in and around the DBR?

1.6 Research Hypotheses

(i) Tree species diversity and composition in DBR and growth of *B. aegyptiaca* have severely been decreased in the areas disturbed by livestock browsing and illegal harvesting.

(ii) Seedlings of *B. aegyptiaca* are most vulnerable to livestock browsing, followed by saplings and then adult trees.

(iii) Sites disturbed due to illegal cutting of *B. aegyptiaca* branches have lower tree survivals, fruit production, and limited seedling recruitment compared to non-disturbed sites.

(iv) The chemical properties of the soil beneath *B. aegyptiaca* tree crowns decrease in disturbed due to livestock browsing and illegal harvesting.

(v) The income of local communities in and around the reserve is influenced by the decline of the *B. aegyptiaca* population.

1.7 Significance of the Study

Up-to-date information and knowledge about the impacts of anthropogenic disturbances on the trees, shrubs, and their natural regeneration in the BRs are very significant and form a cornerstone for the sustainable management of these species and their protection (Fakhry *et al*., 2020; Kutnar *et al*., 2019; Mohammed *et al*., 2021). This knowledge is scarce and often limited to perennial plants (Hawkins, 2017; Listopad *et al*., 2018; Panagopoulos *et al*., 2019; Wang *et al*., 2019). Therefore, this study examines the effects of livestock browsing and illegal harvesting on the distribution and natural regeneration of *B. aegyptiaca* in DBR. This study forms a baseline foundation for controlling the negative effects of livestock browsing and management of illegal harvesting in the protected areas in Sudan and similar systems. The study findings on the responses of *B. aegyptiaca* seedlings and saplings to livestock browsing can guide the policy-makers to formulate policies that will protect the sensitive stage and enhance its recovery. In addition, it raises awareness among locals, particularly livestock keepers and agro-pastoralists, on the significance of conserving the natural regeneration of *B. aegyptiaca* as a way to sustain other services and goods gained from the species.

Further, this study is of high importance to the national forest corporation, rangelands, and animal production officers, as well as wildlife authority, as it assessed the effects of illegal harvesting on tree survival, fruit production, seedling recruitment, and soil chemical properties, which are core concerns for all above five mentioned disciplines (Abdou *et al*., 2015; Chen & Tang, 2016; Domene *et al*., 2017; Ji *et al*., 2017; Reuter *et al*., 2018). Foresters are interested in the information related to the status of tree survival and fruit production as a principal component for yield regulation planning. Moreover, while seedling recruitment and soil property data are highly preferred by the rangeland management authority, wildlife conservation administration is mainly concerned with conservation aspects. Thus, this study is of high significance to these sectors with various potentials, contributions, and implications.

Moreover, the study findings that come from the investigation of the influences of the possible decline of *B. aegyptiaca* populations on the income and livelihood of the local community will pave the way for a permanent solution for this constrain and determines the possible alternatives that can supplement and reduces the pressure on *B. aegyptiaca*.

1.8 Delineation of the Study

The present study was carried out to explore the impacts of livestock browsing and illegal harvesting on the natural regeneration of *B. aegyptiaca* using disturbed and non-disturbed sites in the DBR. A stratified sampling design was used to localize the disturbed and non-disturbed sites, and simple random sampling was used to select the sample plots within different browsed sites. The dendrometric parameters of seedlings, saplings, and adult trees were measured to assess the abundance, density, distribution, basal area contribution, and the proportion of juveniles to adults in each site. The study further collected soil samples under affected and healthy trees to understand the contribution of trees and their crowns to the chemical properties of the soil and how these properties of soil varies. Moreover, the study focused on *B. aegyptiaca* because it is a multipurpose tree species and is widely used by the local community, and their populations are declining across the country.

The study stratified the browsed sites based on the main livestock species that dominated the site as the study aimed at identifying the most damaging livestock species and the sensitive stage of *B.aegyptiaca* to their browsing activities.

CHAPTER TWO

LITERATURE REVIEW

2.1 Biology of *Balanites aegyptiaca*

Balanites aegyptiaca (L) Del., is a medium-sized evergreen tree that usually reaches the average height of 9 m and rarely 15 m, and a mean diameter at breast height of 35 cm (Chothani & Vaghasiya, 2011; Ibrahim *et al*., 2015; Ibrahim & Hassan, 2015). Although the species generally well-known as Desert date, it has several other local names such as Soap berry tree, Thorn tree, and Hegleig (Elbadawi *et al*., 2017; Fadl, 2015; Sagna *et al*., 2014). The Desert date tree is a member of the *Balanitaceae* family, which formerly belonged to *Zygophyllaceae* (Elfeel *et al*., 2007; Fadl, 2015; Ouédraogo *et al*., 2019).

The tree crown is characterized by a spherical to irregular shape with varied crown width and height based on the site conditions and the stage of development (Ibrahim *et al*., 2015; Mohammed *et al*., 2021; Okia, 2013) (Plate 1). While the bark of saplings and juvenile trees is smooth and green in colour, it is rough and deeply fissured with dark brown to greyish colour in the adult trees (Chothani & Vaghasiya, 2011; Fadl, 2015; Khamis *et al*., 2016) (Plate 2).

Plate 1: Crown Shape of Adult *B. aegyptiaca* Trees that have been Measured in Non-disturbed sites of Dinder Biosphere Reserve from January 2019 to December 2020

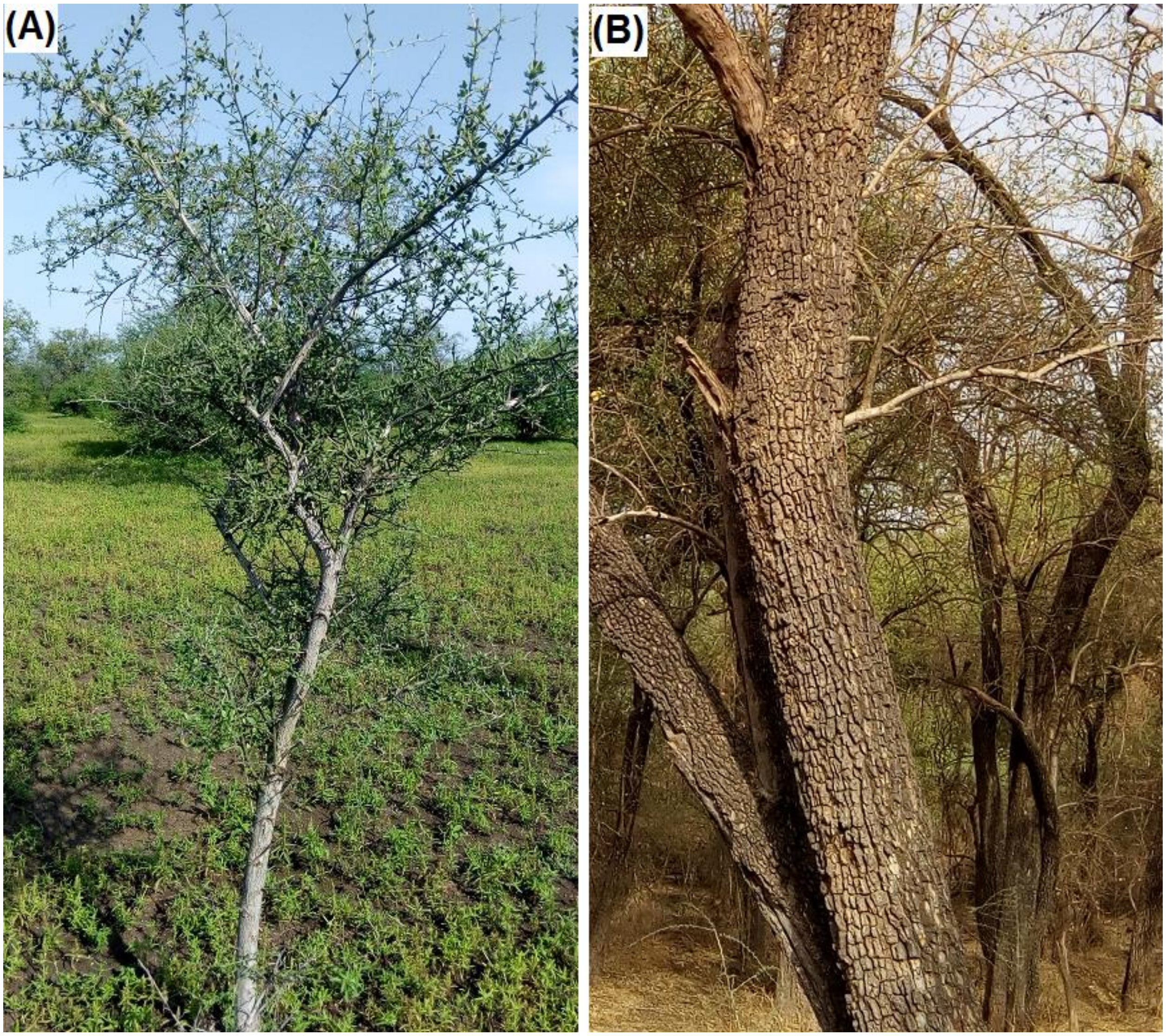

Plate 2: **Illustrates the Outward Bark Appearance and Colour for Sapling and Adult Tree of *B. aegyptiaca*; (A) and (B), Respectively; that have been Assessed in the Non-disturbed Sites of Dinder Biosphere Reserve from January 2019 to December 2020**

Furthermore, *B. aegyptiaca* is characterized by its edible fruits, leaf with two ovate to rhomboid leaflets, and thorny seedlings and saplings (Chothani & Vaghasiya, 2011; Elfeel, 2010; Idrissa *et al*., 2018) (Plate 3). Besides that also, it's a drought-tolerant and multi-purpose tree species with diversified food, feed, medicinal, and agroforestry uses (Hassanin *et al*., 2018; Ibrahim & Hassan, 2015; Mohammed *et al*., 2021) (Plate 4). However, studies on the species response to anthropogenic activities like overgrazing and illegal harvesting are lacking and need to be addressed towards its sustainable management.

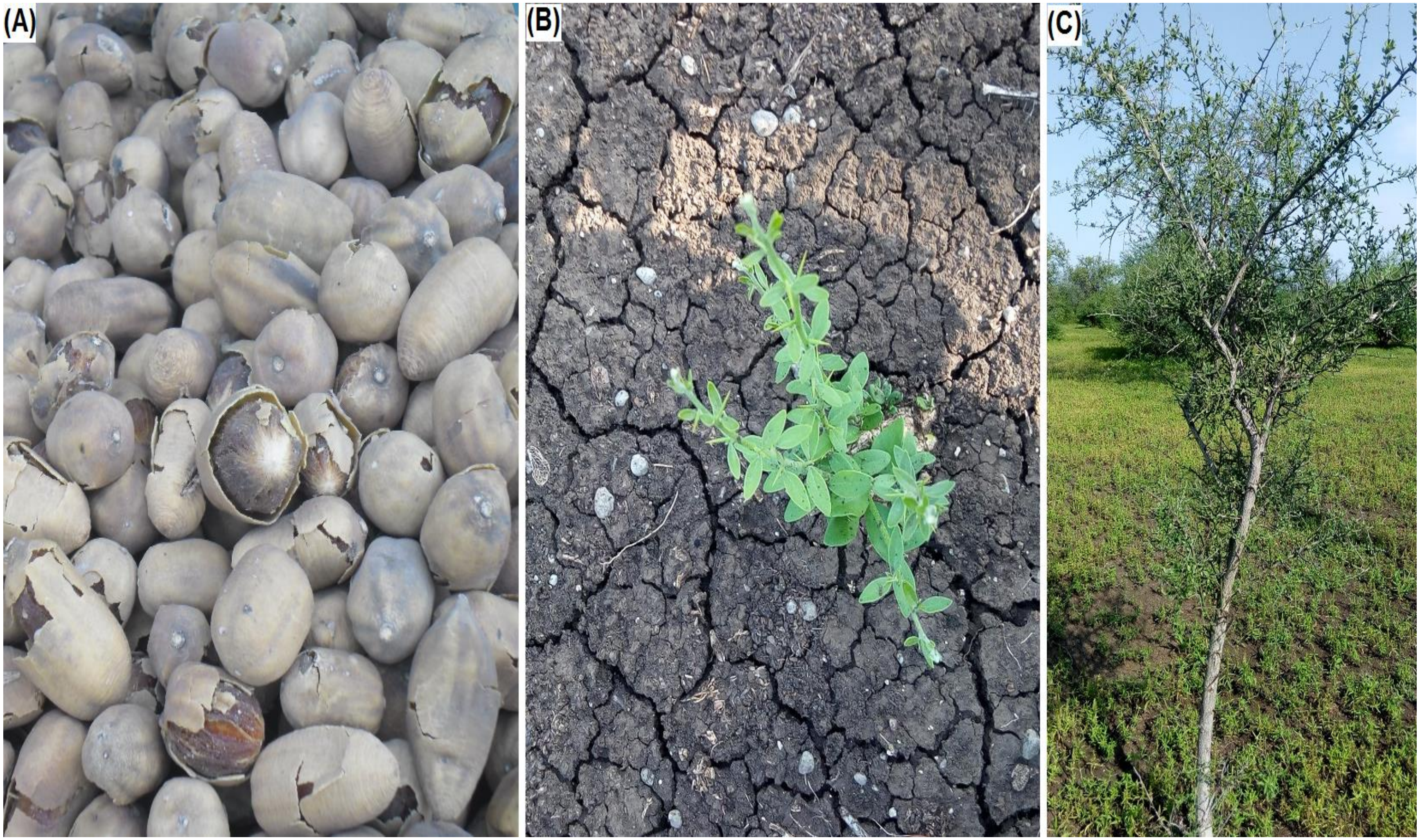

Plate 3: Displays; (A) the Fruits, (B) Seedling, and (C) Sapling of *B. aegyptiaca* Tree Species that have been Collected and Assessed in the Non-disturbed Sites of Dinder Biosphere Reserve from January 2019 to December 2020

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Plate 4: Shows a Population of *B. aegyptiaca* Tree Species Grown in the Drought Area at the Western Part of Dinder Biosphere Reserve that we have Measured at the Period from January 2019 to December 2020

2.2 Global distribution of *Balanites aegyptiaca*

Balanites aegyptiaca (Desert date tree) is native to most arid and semi-arid areas in Africa, with high spread and wealthy stands from north to south (Elfeel, 2010; Idrissa *et al*., 2018; Sagna *et al*., 2014). The species is also indigenous to the Middle East and many Asian countries such as India (Chothani & Vaghasiya, 2011; Okia, 2013), Pakistan (Abdelaziz *et al*., 2020; Manji *et al*., 2013), Iran (Elfeel, 2010; Ouédraogo *et al*., 2019), and Saudi Arabia (Abdelaziz *et al*., 2020; Murthy *et al*., 2021), Syria (Joel, 2018; Murthy *et al*., 2021), and Yemen (Chapagain *et al*., 2009; Elbadawi *et al*., 2017; Fadl, 2015; Murthy *et al*., 2021). Moreover, in Sudan, *B. aegyptiaca* covered a wide distribution range varying from arid lands in the northern part of the country to the semi-arid ones on the west and east as well as the highly fertile ones in the central and southern regions (Adam *et al*., 2013; Elfeel *et al*., 2007; Gasmalla *et al*., 2016; Hasoba *et al*., 2020; Mohammed *et al*., 2021). The species was also introduced in Latin America, Caribbean islands, and Burma (Gebru *et al*., 2019; Joel, 2018; Marone *et al*., 2017; Weber & Montes, 2010). Despite this global distribution of the species, detailed studies on its population structure and its natural regeneration in the Sahel are holistically missing and need to be explored.

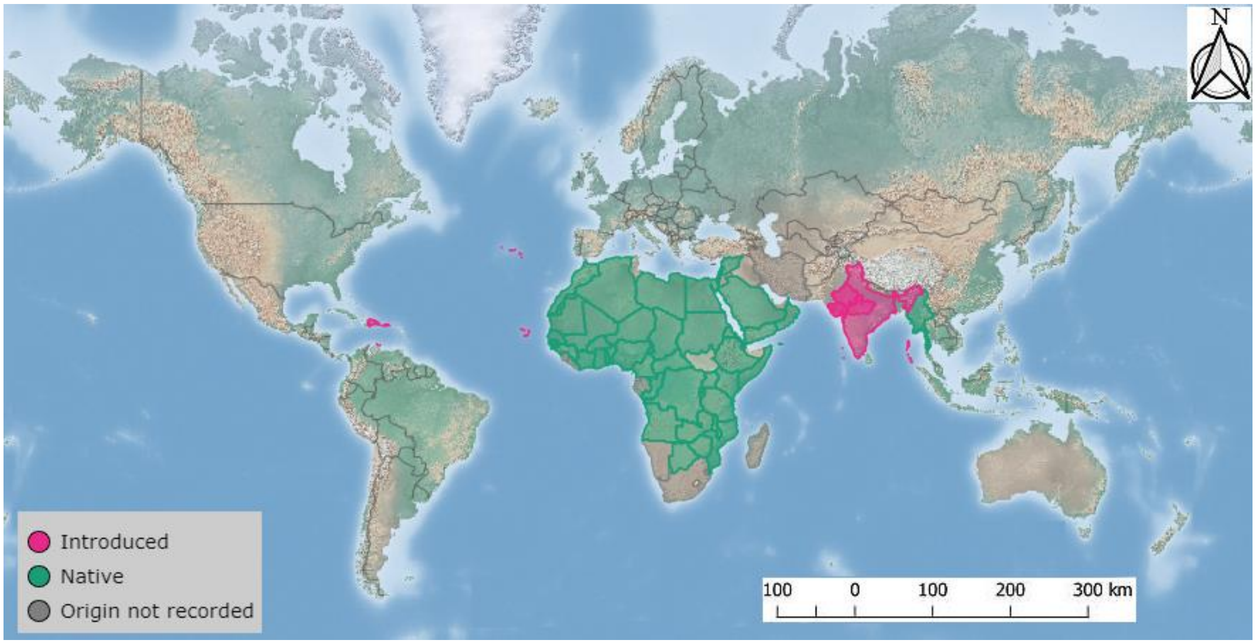

Figure 1: Global Distribution of *B. aegyptiaca*. The Green Areas Show where *B. aegyptiaca* is Native, while the Red-purple Areas indicate Sites where the Species has been Introduced. Moreover, the Grey Areas Illustrate where the Species has never been Recorded (Centre for Agriculture and Bioscience International [CABI], 2021)

2.3 Uses of *Balanites aegyptiaca*

2.3.1 Food and Feed uses

Balanites aegyptiaca has been used for a long time for food and feed purposes among different communities especially in Africa and Asia (Abou-Khalil *et al*., 2016; Elbadawi *et al*., 2017; Hasoba *et al*., 2020; Idrissa *et al*., 2018; Murthy *et al*., 2021). Its fruits are edible, where they can be eaten fresh or dried or even as juice and beverages (Chothani & Vaghasiya, 2011; Fadl, 2015; Ogala *et al*., 2018; Okia, 2013; Ouédraogo *et al*., 2019). However, in some countries like Eritrea, Ethiopia, Kenya, and Uganda, locals also eat the fruits of *B. aegyptiaca* after been cooked and skinned (Beche *et al*., 2016; Okia, 2013; Sagna *et al*., 2014; Tesfaye, 2015). Moreover, other studies have reported that the flowers, leaves, young twigs, and seed kernels of *B. aegyptiaca* tree species also utilized fresh in form of salad or cooked with salt and some seasoning materials to enhance its palatability (Gasmalla *et al*., 2016; Joel, 2018; Khamis *et al*., 2016; Lockett *et al*., 2000; Manji *et al*., 2013). Besides that, its foliage and new shoot are usually used as fodder for livestock in the Sahel region and most sub-Saharan countries, particularly during dry seasons (Elfeel *et al*., 2007; Ibrahim *et al*., 2015; Idrissa *et al*., 2018; Mohammed *et al*., 2021).

2.3.2 Medicinal Uses

The desert date tree is of tremendous medicinal significance, and most of its parts encompass useful compounds that have been used to cure various diseases that attack humankind (Abdel-Motaal *et al*., 2015; Elbadawi *et al*., 2017; Ogala *et al*., 2018; Siddique & Anis, 2009). Extracts from leaves, bark, roots, and fruits have been used to treat Malaria, diarrhea, fevers, and stomach illness (Beche *et al*., 2016; Chothani & Vaghasiya, 2011; Elfeel *et al*., 2007; Elfeel, 2010; Hassanin *et al*., 2018). The fruits and seed kernels of *B. aegyptiaca* are rich with Steroidal secondary metabolizes such as diosgenin and daponins, which are key elements in the production of Corticosteriols, human fertility hormones, and some sterility prevention drugs (Khamis *et al*., 2016; Murthy *et al*., 2021; Ouédraogo *et al*., 2019; Siddique & Anis, 2009).

Further, extracts from Balanites leaves proved to have antioxidant, antimicrobial, and antiprotozoal activity (Al-thobaiti & Abu Zeid, 2018; Elfeel & Warrag, 2011; Khamis *et al*., 2020; Ndoye *et al*., 2004). Antimicrobial activity was investigated against *Streptococcus mutans* and *Escherichia coli,* while antiprotozoal activity was tested against *Trypanosoma cruzi* (Khamis *et al*., 2020). Besides that also, Abdelaziz *et al*. (2020), Alansari & Al-thobaiti (2021), Harlev *et al*. (2012); Hassan *et al*. (2016) and Khamis *et al*. (2020) concluded that secondary metabolizes extracted from *B. aegyptiaca* shoot have a curative significant role as an anticancer. Additionally, derivatives from its bark proved their potentials to cure yellow fever, as well as jaundice and syphilis (Hassan *et al*., 2016; Joel, 2018; Okia, 2013; Tesfaye, 2015). While some studies have reported and proved the uses of aqueous leaf and fruit extracts of *B. aegyptiaca* as an antifungal (Abdallah *et al*., 2012; Khatoon *et al*., 2013; Sawadogo *et al*., 2020; Singh *et al*., 2017), others illustrated their antibacterial and anti-inflammatory potentiality (Ezemokwe *et al*., 2020; Khamis *et al*., 2020; Murthy *et al*., 2021; Tula *et al*., 2014).

Moreover, various studies illustrate the intensive utilization of *B. aegyptiaca* in traditional medicine in many African countries including, Sudan (Hasoba *et al*., 2020; Mohammed *et al*., 2021), Niger (Idrissa *et al*., 2018; Weber & Montes, 2010), Nigeria (Lockett *et al*., 2000; Suleiman *et al*., 2017), Burkina Faso (Nacoulma *et al*., 2016; Ouédraogo *et al*., 2019; Sanon *et al*., 2007), Ethiopia (Beche *et al*., 2016; Gebeyehu *et al*., 2019; Tesfaye, 2015), Uganda (Okia, 2013; Ssegawa & Kasenene, 2007), Kenya (Maua *et al*., 2020), Tanzania (John *et al*., 2020; Kikoti & Mligo, 2015), and Madagascar (Joel, 2018; Murthy *et al*., 2021; Reuter *et al*., 2018).

2.3.3 Agroforestry Uses

Agroforestry is a practice and land use model where trees, shrubs, and other perennials woody plants are integrated with crop and livestock production in the same land-use system (Dawson *et al*., 2009; Endale *et al*., 2017; Poudel *et al*., 2019). Planting in rows, strips, intercropping, and Tungya are various forms of this practice (Folega *et al*., 2011; Idrissa *et al*., 2018; Marone *et al*., 2017). Thus, agroforestry is an innovative way of managing a diversified community of plants and animals to obtains sustained goods and services while conserving biodiversity and enhancing ecosystem resilience (Hollingsworth *et al*., 2005; Idrissa *et al*., 2018; Marone *et al*., 2017; Mohammed *et al*., 2021). Tree species like *Acacia senegal*, *Acacia nilotica*, *Adansonia digitata*, *Balanites aegyptiaca*, *Cordia africana*, *Faidherbia albida*, *Eucalyptus camaldulensis*, *Khaya senegalensis*, *Tamarindus indica*, *Tectona grandis*, and *Ziziphus spina-christi* are among the commonly used tree in agroforestry (Dawson *et al*., 2009; Folega *et al*., 2011; Githae *et al*., 2011; Idrissa *et al*., 2018; Omar & Muhammad, 2016). Moreover, the frequently used tree species for this purpose in the Sahelian region are *A. senegal*, *B. aegyptiaca*, and *F. albida* (Assogbadjo *et al*., 2010; Endale *et al*., 2017; Gebeyehu *et al*., 2019; Idrissa *et al*., 2018).

Researchers reported that farmers in the eastern part of Sudan are planting sorghum (*Sorghum bicolor*) and sesame (*Sesamum indicum*) under *B. aegyptiaca* trees, while in the western region *A. senegal* and *F. albida* are the dominant tree species in their local gardens (Elagib & Al-Saidi, 2020; Fadl *et al*., 2015; Fahmi *et al*., 2018; Magid *et al*., 2014). Also, Elhadi *et al*. (2014) and Fadl *et al*. (2015) reported the intercropping of millet (*Pennisetum glaucum*), groundnut (*Arachis hypogaea*), and watermelon (*Citrullus lanatus*) with scattered *B. aegyptiaca* and *Z. spina-christi* in North Kordofan State, Sudan. Ali *et al*. (2009), Fahmi *et al*. (2015) and Rahim *et al*. (2007) mentioned the frequent practices of growing roselle (*Hibiscus sabdariffa*), sorghum (*Sorghum bicolor*), groundnut (*Arachis hypogaea*), and millet (*Pennisetum glaucum*) in associations with *B. aegyptiaca* and *A. senegal* as a soil fertility improver in the Blue Nile region, Sudan.

Furthermore, some studies illustrated the importance of *B. aegyptiaca* trees to crops as an attractor of insect pollinators (Dawson *et al*., 2009; Idrissa *et al*., 2018; Ndoye *et al*., 2004; Okia, 2013; Weber & Montes, 2010). Windbreaks, shelter, and moderation of harsh weather are also useful functions of *B. aegyptiaca* in the agroforest parklands and rain-fed farms (Elfeel & Warrag, 2011; Fahmi, 2017; Joel, 2018). Moreover, various studies across African countries such as (Gebru *et al*., 2019; Yirga, 2019) in Ethiopia, (Omar & Muhammad, 2016) in Nigeria, (Ssegawa & Kasenene, 2007; Weldemariam *et al*., 2017) in Uganda, (Degrande *et al*., 2006) in

Cameroon, (Asigbaase *et al*., 2019; Hassan & Tag, 2017; Maua *et al*., 2020) in Kenya, and (Haarmeyer *et al*., 2013; Nacoulma *et al*., 2016; Neya *et al*., 2019) in Burkina Faso, discussed the significance of *B. aegyptiaca* as vital agroforestry tree that offering multi-services ranging from improving soil fertility and aeration to the enhancement of farmers livelihood and raising their income. Thus, any recent study that can reveal outcomes related to the population of this valuable species, its structure, natural regeneration, and dynamics is of high significance.

2.3.4 Other Uses

The seeds of *B. aegyptiaca* have a good content of oil which is edible and used locally for making food (Abdelaziz *et al*., 2020; Hasoba *et al*., 2020; Mohammed *et al*., 2021). The oil also used in the manufacturing of some soaps (Chothani & Vaghasiya, 2011; Elfeel, 2010), shampoo (Manji *et al*., 2013; Ouédraogo *et al*., 2019), and various cosmetic products (Beche *et al*., 2016; Elbadawi *et al*., 2017), as well as for biodiesel production and energy derivatives (Chapagain *et al*., 2009; Elfeel & Warrag, 2011; Fadl, 2015; Khamis *et al*., 2016). While the fruits are rich in fatty acids, minerals, and proteins, their oil is also used perfectly in detergents (Abdallah *et al*., 2012; Al-thobaiti & Zeid, 2018; Siddique & Anis, 2009).

The mature trees of *B. aegyptiaca* characterized by durable and termite-resistant wood (Okia, 2013; Sagna *et al*., 2014; Weber & Montes, 2010), which is useful for furniture, agricultural tools, building, handicrafts, firewood utilization, and charcoal production (Adam *et al*., 2013; Hassanin *et al*., 2018; Idrissa *et al*., 2018; Marone *et al*., 2017; Mohammed *et al*., 2021). Besides that, the good porosity of its wood makes it easier to be worked and reshaped (Joel, 2018; Weber & Montes, 2010). Additionally, as its timber secrete resin and the bark rich in extractives, *B. aegyptiaca* resins and extractives worked efficiently as insecticide and pesticides with lower harm to the environment (Fahmi *et al*., 2018; Joel, 2018; Zida *et al*., 2018). As the species might be declining (Hassanin *et al*., 2018; Idrissa *et al*., 2018; Mohammed *et al*., 2021), it is of high significance to understand how such decline can affect the local's livelihood.

2.4 Impacts of Livestock Grazing and Browsing on the Natural Regeneration

Natural regeneration can be defined as a process through which new seedlings, coppices, or sprouts are emerging and growing to replace the destroyed and dead ones towards the restocking of the spaced sites and restoration of the degraded lands (Arosa *et al*., 2017; Ghanbari *et al*., 2021; Hammond *et al*., 2021). Therefore, it is a principal and core process by which most plants naturally recruit new generations, compensate for losses, and sustain their population dynamics

(Hanief *et al*., 2016; Lacerda & Kellermann, 2019; Sukhbaatar *et al*., 2019). However, disturbances including livestock grazing and browsing usually interfere with this process and interrupting its sustainability (Lempesi *et al*., 2017; Sales-Baptista *et al*., 2016). Thus, studies on this aspect are well-appreciated as they will form concrete pillars for future conservation, management, and sustainability plans.

Intensive grazing and browsing are among the leading factors that decrease species diversity and degrade rangelands worldwide (Derebe & Girma, 2020; Mohammed *et al*., 2021; Mysterud, 2006). Arid and semi-arid zones show a clear example where overgrazing had led to a dramatic reduction in the herbaceous plants (Fraser *et al*., 2001; Osem *et al*., 2017), lowered the species richness (Chaturvedi *et al*., 2012; Kikoti & Mligo, 2015), reduplicated the impacts of the soil erosion process (Müller *et al*., 2014; Panagopoulos *et al*., 2019), and soil fertility loss (Kosmas *et al*., 2015; Xu *et al*., 2018). While various studies have addressed these impacts on the herbaceous layer, few studies have investigated the response of woody vegetation, i.e., tree seedlings and saplings, to high animal browsing intensities.

In Africa, and especially the sub-Saharan countries and the Sahel region, overgrazing resulting from mammalian herbivores had altered the sustainability of different forest stands and rangelands by disturbing their natural regeneration (Hawkins, 2017; Kgosikoma *et al*., 2013; Treydte *et al*., 2009), compacting the soil (Derebe & Girma, 2020; Krzic *et al*., 2006), and decreasing their seeds bank (Domene *et al*., 2017; Nacoulma *et al*., 2016; Omar & Muhammad, 2016). Different studies that took place in Ethiopia (Mekuria & Aynekulu, 2013), Tanzania (Ligate *et al*., 2019), South Africa (Kgosikoma *et al*., 2013), Burkina Faso (Sanon *et al*., 2007), Nigeria (Ogunwusi *et al*., 2013), Niger (Idrissa *et al*., 2018), and Cameroon (Degrande *et al*., 2006) have documented how livestock overgrazing increased the rate of deforestation, forest fragmentation, and invasive species in the community forests, natural woodlands, and agroforest parklands. However, with all this literature, the information regarding the impact of livestock browsing on juvenile trees is limited.

Sudan has a significant number of livestock herds (Elmekki, 2008; Hassan & Tag, 2017; Mahgoub, 2014), very trace data is available about their effects on the natural regeneration of woody plants and the seedlings recruitment in their rangelands, protected areas, natural forests and open community forests (Ibrahim & Hassan, 2015; Mohammed *et al*., 2021). The study carried out by (Abdelrahim, 2015) in the Blue Nile region, Sudan, mentioned that overgrazing by livestock affected the income and livelihood of forest products dependent families, particularly those mainly dependent on the non-timber forest products including fruits, resins, gum, and honey. Such indirect effect of overgrazing raised the alert on the significance of monitoring and controlling this practice as well as eliminate its consequences, especially in the biosphere reserves as Dinder.

On the other hand, researchers highlighted that light grazing or browsing in the natural rangelands and forests can suppress the closed plant competitors and promotes ungrazed healthy ones (Lempesi *et al*., 2017; Lopez-Sanchez *et al*., 2014; Müller *et al*., 2014). However, this regime of grazing is achievable only under a restricted monitoring management plan based on the carrying capacity of the site (Gamoun *et al*., 2015; Mysterud, 2006) and the availability of the resources (Hawkins, 2017; Ligate *et al*., 2019; Wang *et al*., 2019). Therefore, information on the species composition, population structure, stocking density, and natural regeneration status are among the leading factors that shape the formulation of a comprehensive plan, which considers the resources sustainability and well-regulated yield.

Studies concerned with the effects of overgrazing on the natural regeneration of *B. aegyptiaca* are scarce or not well-reported. Documents on how seedlings and saplings of this species have been influenced by intensive livestock browsing and frequent grazing are limited, particularly for Biosphere Reserves and other protected areas. Therefore, the current study bridges this gap and contributes to knowledge by revealing up-to-date findings related to this multipurpose tree species and this important stage of development.

2.5 Impact of Illegal Harvesting on the Fruit Production and Seedlings Recruitment

The term illegal harvesting has usually been used to refer to all activities that take place in a protected or reserved area without its authority permit, or exceed their permission limits (Ji *et al*., 2017; Piabuo *et al*., 2021; Reboredo, 2013). It covers stem debarking for medicine, shoots and twigs cutting for animal feeding, uprooting, removal crown branches, especially fruited branches as well as logging of the entire tree (Haarmeyer *et al*., 2013; Nacoulma *et al*., 2016). As debarking usually affected the bark of mature trees, branches cutting and removal on the other hand, reduced the number of fruited branches and seedlings distribution and growth (Bondé *et al*., 2019; Nakajima *et al*., 2015; Zahawi & Holl, 2009).

Frequent and intensive stem debarking has severe impacts on the tree structure, wood continuity, wood conductivity, and tree survival (Beltrán-Rodríguez *et al*., 2021; Chaturvedi *et al*., 2012). Although some tree species like *Anogeissus leiocarpus*, *Azadirachta indica*, *Khaya senegalensis*, *Lannea fruticosa*, *Ziziphus spina-christi* can heal and recover the removed part (Assogbadjo *et al*., 2010; Ball & Tzanopoulos, 2020; Beche *et al*., 2016; Haarmeyer *et al*., 2013), others like *Boswellia papyrifera*, *Commiphora africana*, *Crativa adansonii,* and *Sclerocarya birrea*, are sensitive to deep and extreme debarking (Guedje *et al*., 2016; Negussie *et al*., 2008; Nndwammbi *et al*., 2018). In Sudan, particularly in the Blue Nile Region, the bark of *Acacia nilotica*, *B. aegyptiaca*, *Combretum hartmannianum*, *Sterculia setigera*, *Terminalia brownii*, and *Ziziphus abyssinica*, has commonly been used to treat Malaria, fever, stomach pains, and skin wounds (Abdelrahim, 2015; Ibrahim *et al*., 2014; Ibrahim & Hassan, 2015; Mohammed *et al*., 2021). However, to what extent does this utilization affecting *B. aegyptiaca* populations is unknown.

Further, debranching of the tree crown and twigs can thoroughly reduce the tree's capability to produce fruit and lowered the seedling establishment for the tree species that regenerate naturally by seeds (Abdou *et al*., 2015; Lompo *et al*., 2018). Bondé *et al*. (2019) revealed that illegal harvesting affected the population of Shea tree (*Vitellaria paradoxa*) in Burkina Faso and decreased its fruit production capacity by < 40%, and seedlings recruitment by 35%. Moreover, Kikoti *et al*. (2015) and, Kimaro and Lulandala (2013) reported that tree crown debranching and intensive re-browsing of newly emerged shoots led to natural regeneration failure in North Kilimanjaro and reduced the species richness to a critical level in the coastal area.

Although some studies have discussed the effect of illegal harvesting on soil properties (Missanjo & Kamanga-thole, 2014; Sukhbaatar *et al*., 2019), stand density (Chaturvedi *et al*., 2012; Neelo *et al*., 2015; Vayreda *et al*., 2013), and dendrometric parameters (Aleza *et al*., 2018; Lamien *et al*., 2007; Mohammed *et al*., 2021), knowledge of its impact on juvenile tree growth and seedling development and distribution is low. Vulnerable species like *B. aegyptiaca*, with its tremendous uses and services, need more researches in this aspect as a prerequisite for species conservation. Thus, the current study bridges this gap by assessing and analyzing how illegal harvesting influences the natural regeneration, fruit production, and seedling distribution of *B. aegyptiaca* in the Dinder Biosphere Reserve, Sudan.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The study was carried out in Dinder Biosphere Reserve (DBR), which is located in the south-eastern part of Sudan, at latitudes 11º 20′ N and 13º 00′ N and longitudes 34º 30′ E and 35º 48′ E (Fig. 2) with 10 290 km^2 as a total area (Higher Council for Environment and Natural Resources [HCENR], 2004; Mohammed *et al*., 2021). The annual rainfall in DBR varies from 600 mm to 1100 mm between April to November (Mohammed *et al*., 2021; Saaid *et al*., 2019), while the minimum mean monthly temperature range from 18-20 °C, and the maximum between 27 to 44°C (Hassaballah *et al*., 2016; Hassaballah *et al*., 2020). The reserve consists of three zones which are transition, buffer, and core zone (Mahgoub, 2014; Mohammed & Hashim, 2015). The transition zone is the outer zone that protect the Buffer and core zone (Elmekki, 2008; Mohammed *et al*., 2021). The core zone is located at the center of DBR, while the buffer zone is situated between the transition and core zone (Ahmed, 2005; Mahgoub, 2014).

The transition zone is usually under high anthropogenic pressure and frequent disturbances due to the presence of more than 25 villages in the area (Mohammed & Hashim, 2015; Yousif & Mohammed, 2012). The dominant tree species in this zone are *Acacia senegal*, *Acacia seyal*, *B. aegyptiaca*, *Boswellia papyrifera*, *Combretum hartmannianum*, *Lonchocarpus laxiflorus*, and *Ziziphus spina-christi* (Mahgoub, 2014; Mohammed *et al*., 2021). However, in the buffer zone beside the above-mentioned tree species, the site also hosts *Acacia mellifera*, *Acacia polyacantha*, *Anogeissus leiocarpus*, *Combretum ghasalense*, and *Tamarindus indica* (Elmekki, 2008). It also hosts a diversified animal species including, Guinea fowl (*Numida meliagris*), Egyptian goose (*Alopochen aegyptiaca*), common ostrich (*Struthio camelus*), water buck (*Kobus ellipsiprymnus*), and Hussar monkey (*Cercopithecus aethiops*) (Elmekki, 2008; Mahgoub, 2014; Mohammed *et al*., 2021; Wassie, 2011; Yousif, 2012). Although this zone is adjacent to the transition zone, it is subjected to low human disturbances compared to the transition (Hassaballah *et al*., 2016; Mohammed & Hashim, 2015; Yousif & Mohammed, 2012).

The core zone represents the heart of DBR, where the majority of wild animals including, large mammals, carnivores, reptiles, and birds are found (Mohammed *et al*., 2021; Yousif, 2012). It hosts more than 33 tree species which are varying between the deciduous tree species like *Combretum aculeatum*, *Combretum glutinosum*, *Lannea nigritana*, *Lannea schimperi*, *Sclerocarya birrea*, *Sterculia setigera*, and *Terminalia brownii*, and the evergreen trees that includes: *Balanites aegyptiaca*, *Boscia senegalensis*, *Tamarindus indica*, and *Ximenia americana* (Ahmed, 2005; Basheer *et al*., 2016; Saaid *et al*., 2019). Wild animals like reedbuck (*Redunca redunca*), warthogs (*Phacochoerus aethiopicus*), Anubis baboon (*Papio anubis*), roan antelope (*Hippotragus equinus*), and African buffalo (*Syncerus caffer*) are frequently observed in this zone (Mahgoub, 2014; Wassie, 2011). All activities like livestock grazing, timber harvesting, fuelwood production, and poaching are prohibited in this area (Mohammed & Hashim, 2015; Yousif & Mohammed, 2012).

The soil is generally black cracky clay across the biosphere except in the mountainous area at the southern (Tabya) and south-western part (Kadalu), where mixed sandy-clay soil can be found (Basheer *et al*., 2016; Mohammed *et al*., 2021). The common income generation activities of the local communities within and around the reserve are horticulture, agriculture, livestock keeping, firewood and charcoal production, non-timber forest products (NTFPs) collection, and fishing (Ahmed, 2005; Elmekki, 2008; Mahgoub, 2014). While the main agricultural crops in the area are sorghum (*Sorghum bicolor*), sesame (*Sesamum indicum*), milt (*Pennisetum glaucum*), and watermelon (*Citrullus lanatus*); the major livestock species reared by the locals for meat and milk are goats (*Capra hircus*), cattle (*Bos indicus*), sheep (*Ovis aries*), and camels (*Camelus dromedarius*) (Fahmi *et al*., 2015; Fahmi *et al*., 2018; Mahgoub, 2014; Mohammed *et al*., 2021; Raddad *et al*., 2006).

Small sample plots of 5 x 5 m^2 were used for seedling and sapling measurements compared to larger sample plot sizes of 25 x 40 m^2 for adult trees. This multi-approach sampling regime was recommended by several scholars (Grenier *et al*., 2008; Meng, 2013; Pirzadeh *et al*., 2013; Storch *et al*., 2018).

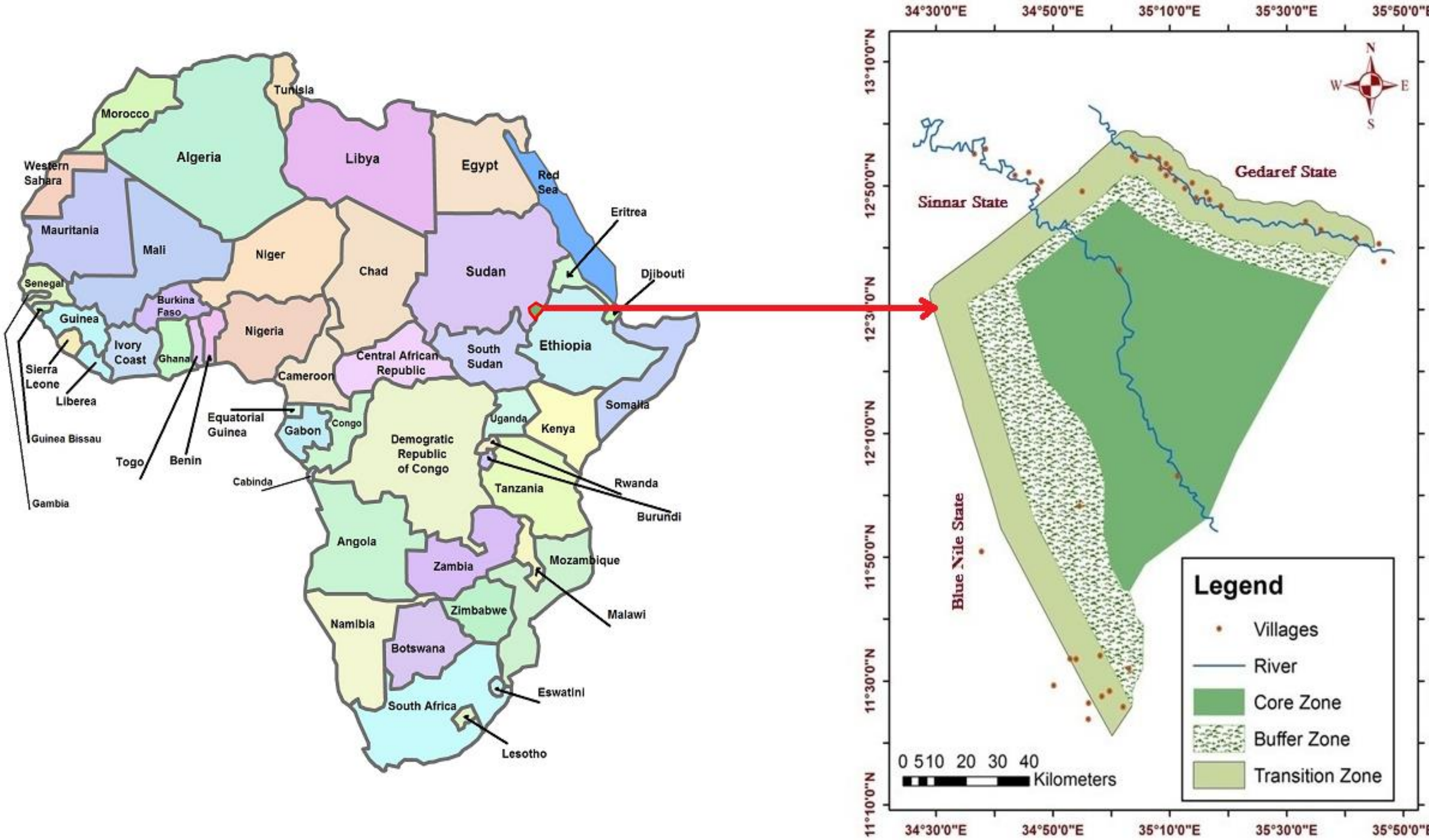

Figure 2: The Map of the Study Area showing the Transition, Buffer, and Core Zone of the Dinder Biosphere Reserve, where we Collected all our Study Data from January 2019 to January 2021

3.2 Exploring the Effects of Livestock Browsing and Illegal Felling on the Tree Species Diversity, Composition, and Growth of *B. aegyptiaca* in Dinder Biosphere Reserve

3.2.1 Data Collection

For data collection, as the transition zone is under high human disturbances, and the core zone is without anthropogenic activities, the study assigned the first one as a disturbed site and the second one as a non-disturbed site. Fifty (50) sample plots were randomly laid in each site that sum up to 100 sample plots across the study area (Fig. 3). These sample plots were rectangular in shape, with a size of 25 m x 40 m, and were measured in the period between April 2019 to April 2020. In each plot, the study identified and classified all the observed tree species and distinguished them into; adult trees, saplings, and seedlings. Adult trees were defined as those with a trunk diameter at breast height (DBH) of ≥ 7 cm (Ibrahim *et al*., 2018; Ibrahim *et al*., 2014; Osman & Idris, 2012). Moreover, saplings are with core diameter (CD) of 3 cm to 6.9 cm (Gebeyehu *et al*., 2019; Kikoti *et al*., 2015; Tripathi & Tripathi, 2010), and seedlings are of < 3 cm core diameter (Lempesi *et al*., 2017; Papadopoulos *et al*., 2017).

Further, four dendrometric parameters (height, DBH, crown width, and crown height) were measured for all adult trees in the sampled sites. Tree DBH was measured using Ordinary Caliper (65 cm) for the small and juvenile trees and tape (5 m) for the largest (Ibrahim & Hassan, 2015; Mohammed *et al*., 2021). Suunto Hypsometer and Spiegel Relaskope were used for total tree height (H) and crown height (CH) measurements, respectively (Ibrahim *et al*., 2015; Ibrahim & Osman, 2014; Idrissa *et al*., 2018). In addition to that, tree crown width (CW) was measured by using a 50 m distance measuring tape at eight directions radiating from the tree base and vertically towards the edges of the tree crown and stand canopy (Assogbadjo *et al*., 2010; Fahmi *et al*., 2018; Ranaivoson *et al*., 2015). The tree identification and nomenclature for all observed and measured tree species were done by a botanist with the help of identification manuals and literature (Nndwammbi *et al*., 2018; Seth, 2004; Weldemariam *et al*., 2017).

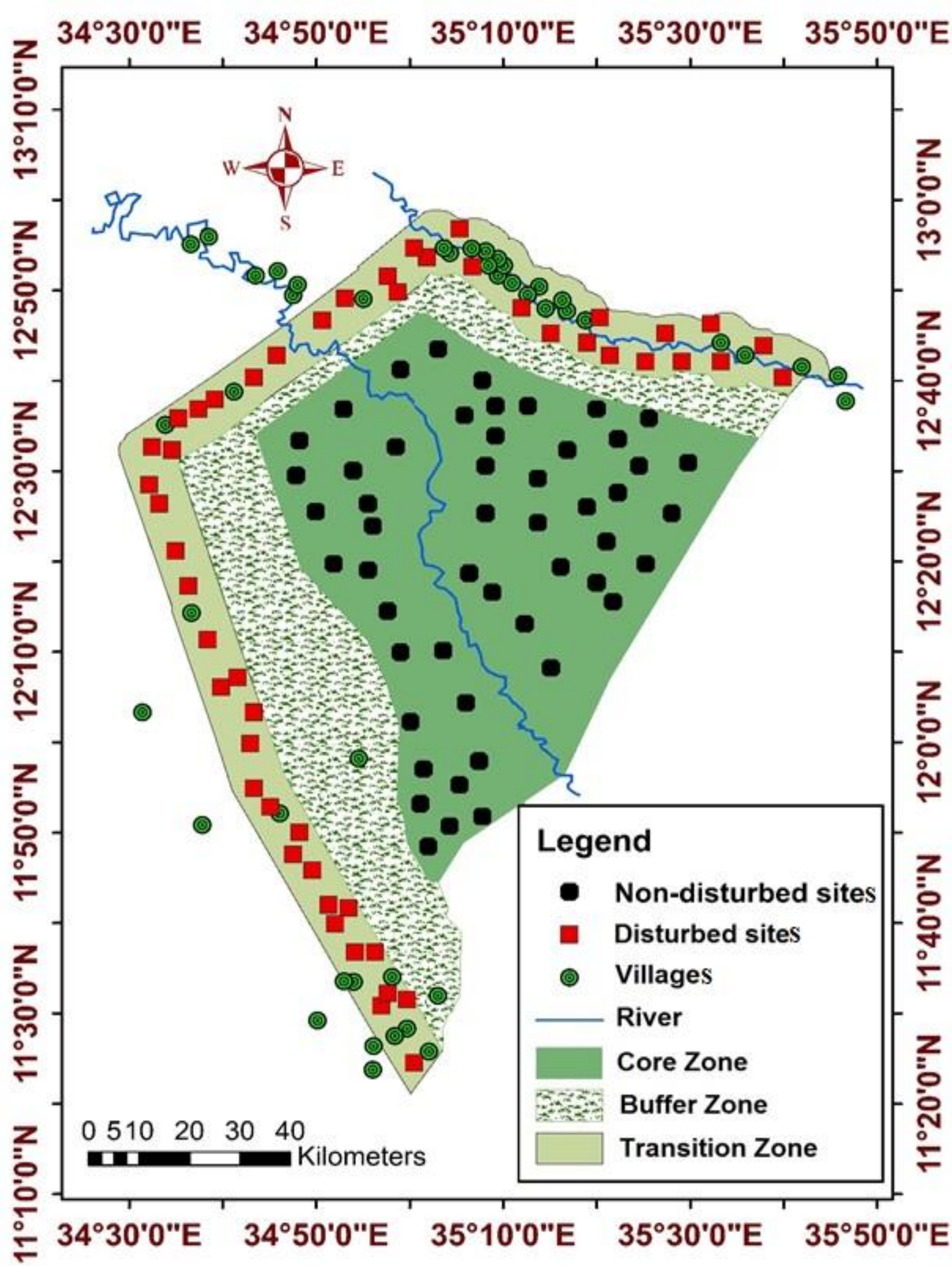

Figure 3: The Map of the Study Area, with the Sampling Locations in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve, where we Assessed the Tree Species Diversity, Composition, and *B. aegyptiaca* Growth (April 2019 to April 2020)

3.2.2 Statistical Analysis

The average DBH, H, and CW were calculated for each sample plot as a prerequisite for further comparison within and between the sites as recommended by Assogbadjo *et al*. (2010), Gebeyehu *et al*. (2019) and Ghanbari *et al*. (2021). Further, the equations in (Table 1) were used to compute the tree density (# of trees/ha), basal area per tree (m^2), relative abundance (%), relative dominance (%), relative frequency (%), and importance value index (IVI) (Ghanbari *et al*., 2021; Idrissa *et al*., 2018; Mohammed *et al*., 2021). Low IVI value shows that no significance and the higher ones illustrate the greatest importance of the species within the population (Hernández *et al*., 2018; Maua *et al*., 2020).

Minitab 17 was used to calculate the mean and coefficient of variation for all measured structural and dendrometric parameters (Mohammed *et al*., 2021). To compare the averages of measured adult trees, saplings, and seedlings, one-way ANOVA using JAMOVI 1.1.7 was run. Moreover, for the comparison of dendrometric parameters across the sites, the study applied a paired sampled *t*-test using JAMOVI, as recommended by Assogbadjo *et al*. (2010), Idrissa *et al*. (2018) and Mohammed *et al*. (2021). The same procedure was performed for diversity indices.

Furthermore, a principal component analysis (PCA) in Past (version 3.6) was performed for the IVI values, based on this study hierarchical cluster analysis (HCA) results. Additionally, to distinguish between size classes of *B. aegyptiaca* tree species in the disturbed and non-disturbed sites of DBR, the study used Weibull distribution in Minitab 17, as also used by Assogbadjo *et al*. (2010), Idrissa *et al*. (2018), Ligate *et al*. (2019) and Mohammed *et al*. (2021).

Table 1: Used Equations for the Computation of Various Structural and Dendrometric Tree Parameters at both Disturbed and Non-disturbed Sites

No	Parameter	Equation	Reference
1	Tree basal area (g)	$g = [\pi * DBH^2] \div 4$	Ibrahim and Hassan (2015)
2	Stand basal area (G)	$G = [n \div 4s] * [\sum DBH^2]$	Idrissa *et al*. (2018)
3	Stand density (N)	$N = n * 1/s$	Assogbadjo *et al*. (2010)
4	Species abundance (A)	A = total # of tree per species ÷ plot area	Osman and Idris (2012)
5	Relative abundance (RA)	RA = [species abundance ÷ total abundance] * 100	Ibrahim *et al*. (2015)
6	Species dominance (D)	D = species total basal area ÷ plot area	Idrissa *et al*. (2018)
7	Relative dominance (RD)	RD = [species dominance ÷ total dominance] * 100	Ibrahim and Hassan (2015)
8	Species frequency (F)	F = presence or absence of a species in the plot	Osman and Idris (2012)
9	Relative frequency (RF)	RF = [species frequency ÷ total frequency] * 100	Osman and Idris (2012)
10	Importance value index (IVI)	IVI = (RA) + (RD) + (RF)	Mohammed *et al*. (2021)
11	Blackman index (IB)	$IB = \sigma_N^2 \div \mu_N$	Mohammed *et al*. (2021)
12	Basal area contribution (Cs)	Cs = [Gs ÷ G] * 100	Mohammed *et al*. (2021)
13	Simpson's evenness (Eq)	Eq = ID ÷ I max, I max = S	Assogbadjo *et al*. (2010)
14	Simpson's reciprocal index (I_D)	$I_D = \frac{1}{\sum_{i=1}^{sp} \frac{n_i(n_i-1)}{n(n-1)}}$	Assogbadjo *et al*. (2010) and Mohammed *et al*. (2021)

DBH is tree diameter at breast height (1.3 m above the ground) measured in cm, *n* is the total number of trees per plot, *s* is the area of the plot, and σ_N^2 and μ_N are variance and of *B. aegyptiaca* density, respectively. G_B and *G* are *B. aegyptiaca* and stand basal area, respectively. *S* is the species richness which was calculated as a number of tree species per site

3.3 Identifying the Sensitive Stage at which *B. aegyptiaca* is most Affected by Livestock Browsing in Dinder Biosphere Reserve

3.3.1 Data Collection

The study stratified the disturbed area (Transition zone) into three sites depending on the major livestock groups reared by local community in the area. For GOA (goat), the major livestock group was goat while for CAT (cattle) and CAM (camel) the dominant groups are cattle and camel, respectively (Fig. 4). At each site browsing animals were assessed either directly or indirectly via signs of animal browsing, type of animal dung, degree of livestock trampling and livestock trespassing records from the annual reports of the DBR administration (2018, 2017, 2016 and 2015) and literature (Elmekki, 2008; Hassan & Tag, 2017; Mahgoub, 2014; Mohammed & Hashim, 2015; Mohammed *et al*., 2021), (Table 2).

Within each site, 50 squared sample plots of 5 x 5 m^2 were located randomly, summing up to a total of 200 sample plots across the reserve. The selection and location of sample plots were based on complete randomization. In each sample plot, the study recorded the number of *B. aegyptiaca* seedlings and saplings and whether they were un-browsed, browsed or dead. A seedling and/or sapling was considered to have been browsed (affected) if any of its branches or leaves had been injured or damaged or removed due to an animal bite (Ibrahim & Hassan, 2015; Kikoti *et al*., 2015; McEvoy *et al*., 2006; Mohammed *et al*., 2021).

For each single browsed seedling and/or sapling, the study recorded and documented the number of branches and twigs, which had recovered or died because of browsing, as well as, the browsing height. Recovery state was mainly judged depending on the occurrence of new leaves and shoots in seedlings and/or saplings after being attacked (browsed) by animals. All fieldwork activities were carried out during the dry season when livestock grazers and browsers were usually available inside the reserve.

Table 2: Livestock Species, their Numbers, and the Total Contribution of Each Species to the Overall Livestock Numbers in the Transition Zone of Dinder Biosphere Reserve (Total %) in the Dry Season

Livestock species	Number	Total %	Dominant in
Cattle	15 400	44.1	CAT
Goat and sheep	15 361	43.9	GOA
Camel	4050	11.6	CAM

Dominant refers to > 50% of the main browser species being composed by that species. CAT = site browsed mainly by cattle, GOA = site browsed mainly by goats, and CAM = site browsed mainly by camels. Fieldwork observation of the author (2019 - 2020), annual reports of DBR administration (2015 - 2018) and (Mohammed & Hashim, 2015; Yousif & Mohammed, 2012)

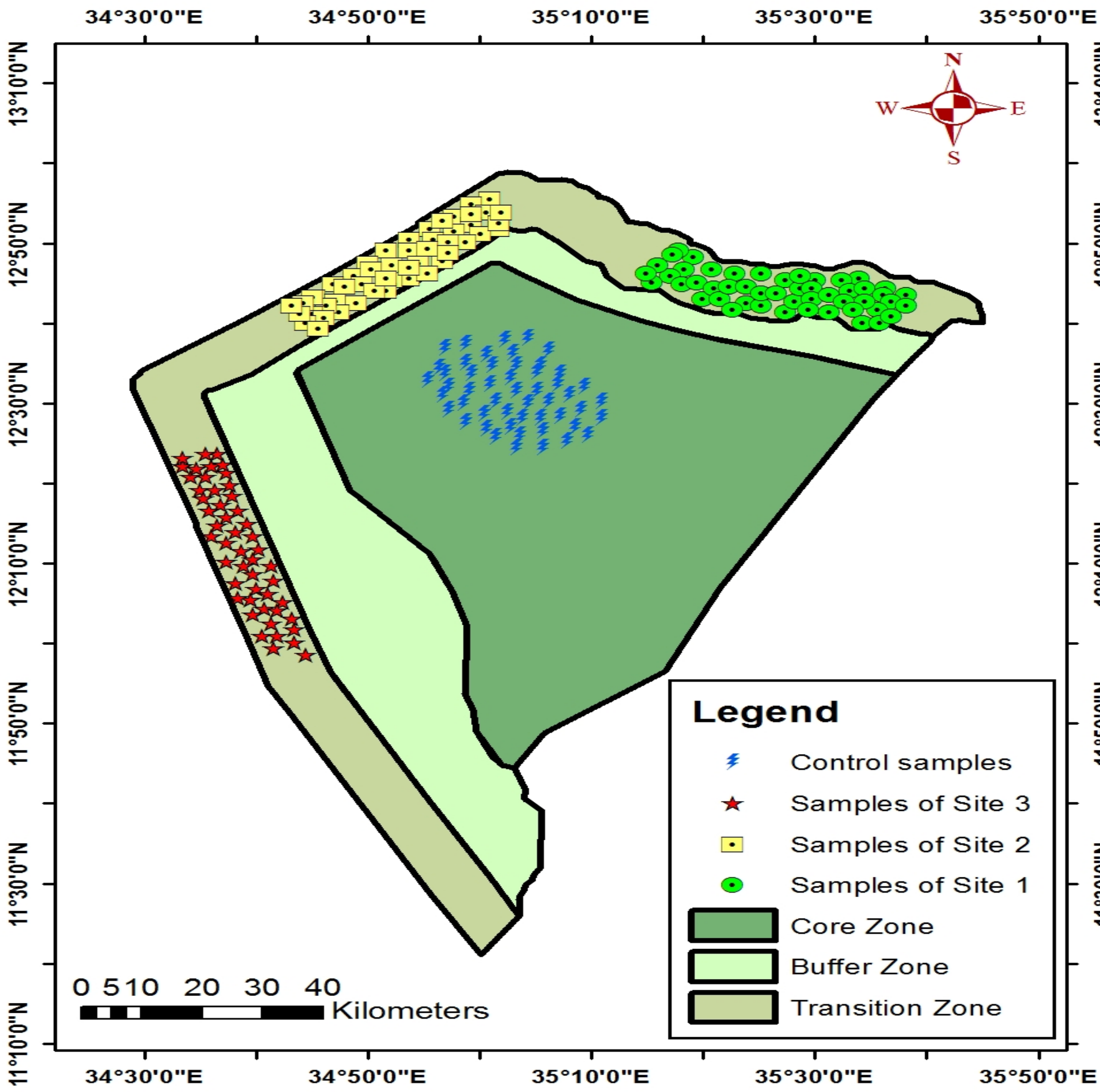

Figure 4: The Map of the Study Area, with its Three Zones. Green rings, Yellow rectangular, Pink stars and Blue bolts indicate the Sample-plots within the four Sampled Sites, i.e., GOA (site browsed mainly by goats), CAT (site browsed mainly by cattle), CAM (site browsed mainly by camels) and CON (control without livestock browsers), respectively

3.3.2 Statistical Analysis

All analysis was performed in JAMOVI (version 1.1.7) and Minitab (version 17). After testing for normality using the Shapiro Wilk test (Missanjo *et al*., 2015; Truong & Marschner, 2018), this study run a one-way analysis of variance (ANOVA) to compare survival, mortality, and recovered seedlings and saplings across different animal browsing categories (Burman *et al*., 2018; Hasoba *et al*., 2020; Jevon *et al*., 2020; Sukhbaatar *et al*., 2019). The Tukey's Post-Hoc tests ($\alpha = 0.05$) was used to compare means (Assogbadjo *et al*., 2010; Fahmi, 2017; Ghosh & Devi, 2019; Mohammed *et al*., 2021).

Descriptive analyses for the common dendrometric parameters of the seedlings and saplings, including diameter, density, and height, were accomplished using Minitab 17 (Kingazi *et al*., 2020; Mohammed *et al*., 2021). To compare the diameter and height mean of the affected and healthy seedlings and saplings, this study used a paired sampled *T*-test (Kingazi *et al*., 2020; Mekuria & Aynekulu, 2013; Müller *et al*., 2014).

Furthermore, to understand the possible correlation between the recovered seedlings and saplings and their sample plot densities across the various browsed sites in the reserve, the current study interrelated the total height of seedlings and saplings with their density using JAMOVI 1.1.7, as per Domene *et al*. (2017), Ghosh & Devi (2019) and Hasnain *et al*. (2020).

3.4 Assessing the Effect of Illegal Cutting of *B. aegyptiaca* Branches on Tree Survival, Fruit Production, and Seedling Recruitment in Dinder Biosphere Reserve

3.4.1 Data Collection

The study area was inventoried using a simple random sampling technique with rectangular sample plots of 25 m x 40 m (1000 m^2). A total of 100 sample plots were laid out across the study area, 50 each in the disturbed and undisturbed sites, respectively, from February 2020 to February 2021 (Fig. 5). At each sample plot, all tree species were identified and the diameter at breast height (DBH), total tree height (H), and crown width (CW) were measured for mature trees (> 7 cm in DBH) (Ibrahim *et al*., 2018; Osman & Idris, 2012). Caliper, Suunto clinometer, and tape were used for measuring DBH, H, and CW, respectively (Ibrahim & Osman, 2014; Missanjo *et al*., 2015). The CW was measured in eight directions from the tree bole every 45 degrees to the vertically projected edge of the tree crown (Ibrahim *et al*., 2015).

To quantify the average number of fruiting branches (FB) per tree at each sample plot in the disturbed and undisturbed sites, the study randomly selected five adult trees for both *B. aegyptiaca* and other tree species (ten trees per sample plot), and all fruiting branches were counted side by side in a clockwise direction and recorded (Missanjo *et al*., 2015; Nakajima *et al*., 2015; Singh & Kushwaha, 2006; Wich *et al*., 2011). Also, the study counted and recorded the number of seedlings and saplings for each sample plot.

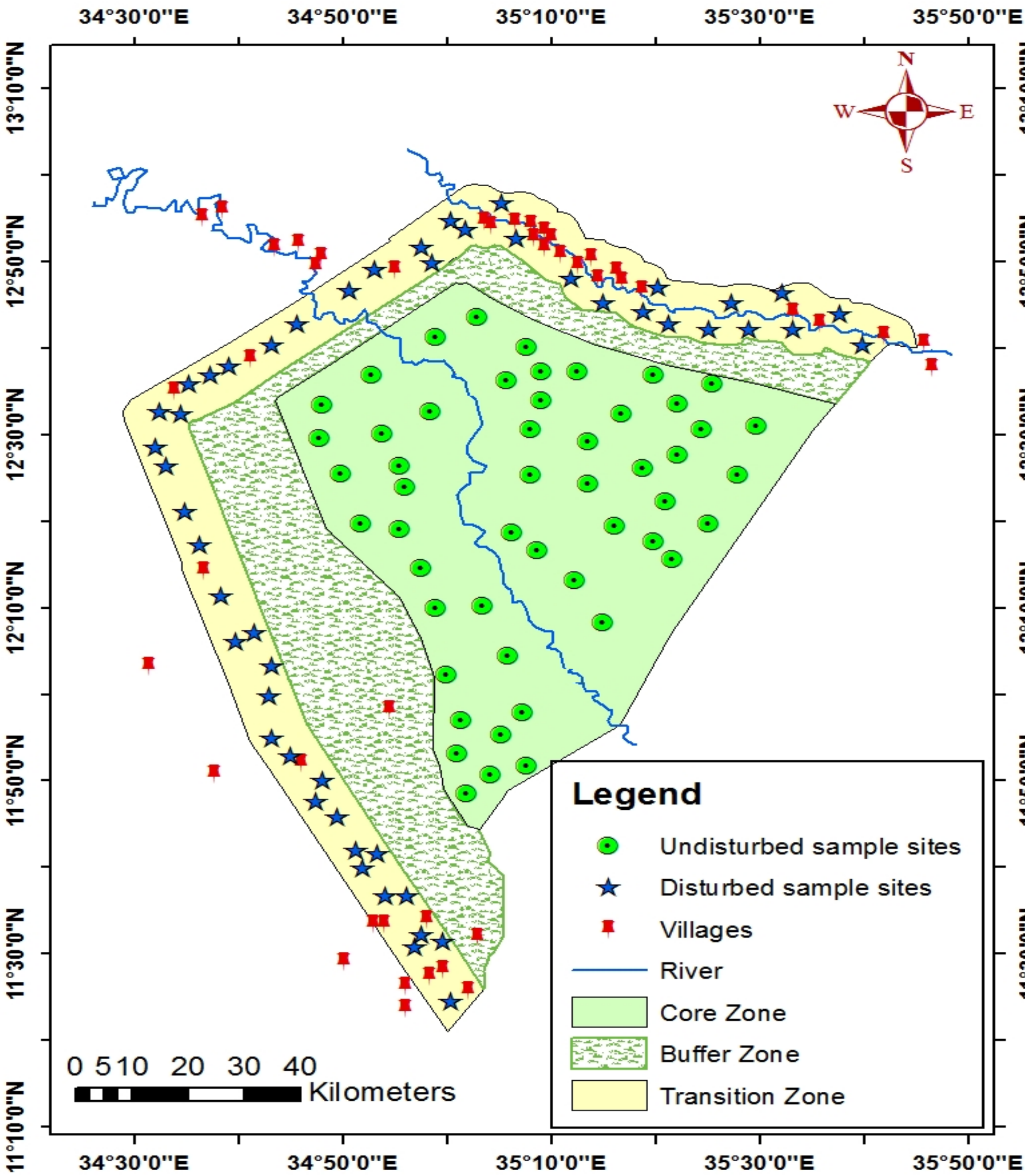

Figure 5: The Map of the Study Area, with the Sampling Locations in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve, where We Assessed the Tree Crown Width, Fruited Branches, and Seedlings Recruitment for *B. aegyptiaca* and Other Tree Species (February 2020 to February 2021)

3.4.2 Statistical Analysis

Normality and homogeneity tests were done using Shapiro Wilk and Kolmogorov-Smirnov D tests, respectively (Missanjo *et al*., 2015; Truong & Marschner, 2018). Two-way ANOVA was used to analyze the data of DBH, H, and CW variables within and between the disturbed and undisturbed sites across the study area (Ghosh & Devi, 2019; Hasnain *et al*., 2020). To explore the association between the tree crown width and the number of seedlings and saplings under trees, the study used regression analysis with JAMOVI software (version 1.1.7) (Hasnain *et al*., 2020). The same procedure was used to correlate the average number of fruiting branches of *B. aegyptiaca* to its crown width. To distinguish the significant differences between different measured variables in the studied sites, Tukey's tests at $\alpha = 0.05$ was used (Ghosh & Devi, 2019; Truong & Marschner, 2018). All statistical analyses were performed using JAMOVI (version 1.1.7) and Minitab (version 17).

3.5 Quantifying the Differences in the Soil Chemical Properties Beneath the Affected and Healthy Trees in Dinder Biosphere Reserve

3.5.1 Data Collection

100 rectangular sample plots, with an area of 25 m x 40 m were randomly laid out, 50 samples in the disturbed, and the same in the non-disturbed site, in a period from February 2020 to February 2021 (Fig. 5). In each sample plots, the study collected two soil samples: one sample under a *B. aegyptiaca* tree and another one under a different tree species within the same sample plot. All soil samples were gathered in the dry season with an auger instrument at a depth of 0 – 30 cm and 5 cm width (0.5 kg) (Sigaye *et al*., 2020; Toledo *et al*., 2011; Wang *et al*., 2020), summing up to 200 samples. All soil analyses were performed in the laboratory of the soil department at the University of Gezira, where pH, N, Na, K, P, C/N, SOC, and Electrical Conductivity (ECe), all were analyzed using the recommended standard procedures (Hofhansl *et al*., 2020; Sigaye *et al*., 2020).

Nitrogen and Organic carbon were measured with a CN-analyzer (Scholten *et al*., 2017). Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) with nitric and perchloric acid were also used to measure the concentrations of P, Na, and K (Hofhansl *et al*., 2020; Scholten *et al*., 2017). Moreover, the soil pH was measused by using an ion-sensitive field-effect transistor (ISFET) with a soil to water ratio of 1:2 as recommended by Hofhansl *et al*. (2020), while electric conductivity was measured with a soil conductivity tester (Heshmati *et al*., 2018; Sukhbaatar *et al*., 2019). Carbon:Nitrogen ratio was calculated as an atomic ratio using organic carbon to nitrogen (Yang *et al*., 2019).

3.5.2 Statistical Analysis

Two-way ANOVA in JAMOVI 1.1.7 was performed to analyze the various soil variables within and between the sites. The Shapiro Wilk test was applied to check for normality (Missanjo *et al*., 2015; Mohammed *et al*., 2021) and the Kolmogorov-Smirnov test for homogeneity (Joel, 2018; Missanjo *et al*., 2015; Truong & Marschner, 2018). Regression analysis in Minitab 17 was carried out to examine the correlation between the tree crown width and the chemical properties of the soil (particularly; N, SOC, K, P, Na, and C/N) in the disturbed and non-disturbed sites. Besides that, the study also run Tukey's tests at $p = 0.05$ to explore the significant differences among the various soil variables, as recommended by Burman *et al*. (2018), Ghosh & Devi (2019), Mohammed *et al*. (2021) and Truong & Marschner (2018).

3.6 Evaluating the Influence of *B. aegyptiaca* population Decline on the Income of Local People within and Around Dinder Biosphere Reserve

3.6.1 Data Collection

To assess the contribution of *B. aegyptiaca* tree species to the forest-based livelihoods and household income within and around the DBR, and how the expected decline of the species population will affect the locals, this study held a key informants interview and conducted a semi-structured questionnaire (Abdelaziz *et al*., 2020; Rahman *et al*., 2016; Williamson, 2017). The study purposively interviewed the chiefs of the selected villages (n = 9), forest management officers (n = 3), rangelands management officers (n = 3), and wildlife authority officers (n = 5) to get their views on the uses of NTFPs in the area and its decline can influence the local community (Beiske, 2007; Ibrahim *et al*., 2015). Nine villages were selected for administrating the questionnaire, and selection was based on the main income generation activities of the locals and the locations of these villages (Beiske, 2007; Deafalla *et al*., 2014; Williamson, 2017). The selected villages are Um-Elkheir, Nor-Elmadeina, Elkhairat, Korwash, Gari, Um-Bagara, Gadaf, Amri, and Mokla (Fig. 6). The questionnaires covered 270 individuals as 30 respondents from each village, with good consideration to the gender and age balance among the participants. The questionnaire involved 24 components, covering the demographic characteristics of the participants, their socio-economic activities, their experience in uses, markets, and selling of *B.*

aegyptiaca products, the history of the species in the area, alternative species with similar benefits, and the consequences of the species decline on their life (Appendix 1).

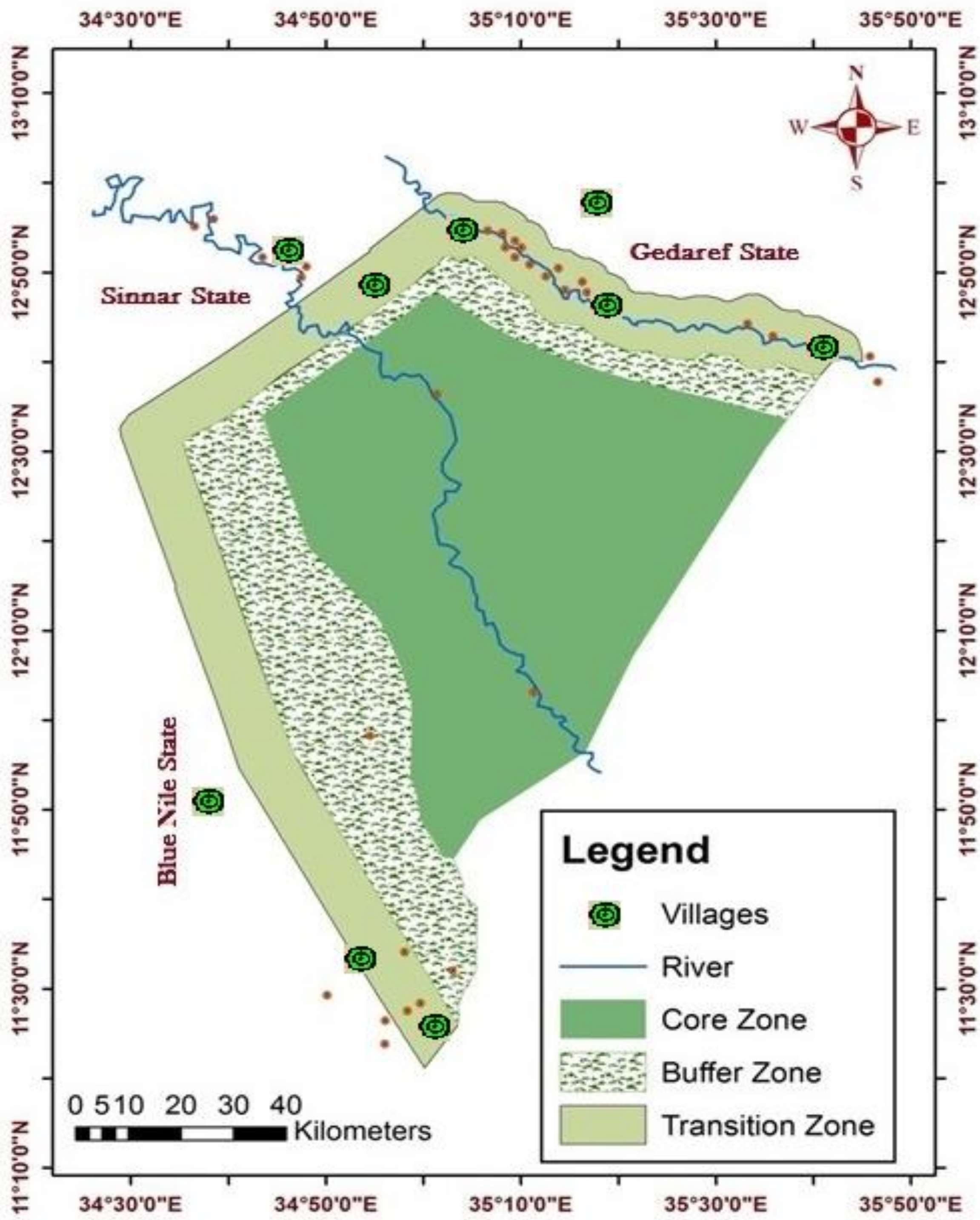

Figure 6: Map of the Study Area illustrating the Three Zones of Dinder Biosphere Reserve and the Location of Selected Villages for Questionnaire and Interviews

3.6.2 Statistical Analysis

All gathered information during the key informant interviews and semi-structured questionnaires were coded, organized, and categorized before been analyzed using IBM SPSS (version 24.0) (Ahenkan & Boon, 2011; Rahman *et al*., 2016; Williamson, 2017). Descriptive statistics, cross-tabulation, and analysis of variance (ANOVA) were performed to compare, distinguish, and correlate the demographic characteristics and the socio-economic activities with the species uses, received revenue, and the constraints (Beiske, 2007; Okia, 2013; Williamson, 2017).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Exploring the Effects of Livestock Browsing and Illegal Felling on the Tree Species Diversity, Composition, and Growth of *B. aegyptiaca* in Dinder Biosphere Reserve

(i) High Diversity and Tree Density in Non-disturbed Site

Tree species richness in the non-disturbed site was double that in disturbed site ($p < 0.001$, $T = 18.6$), while diversity index and Simpson's evenness index were more than twice ($p < 0.001$, $T = 33.2$; and $p < 0.05$, $T = 28.2$, respectively; Table 3). The density of the five most dominant mature trees ($F_{6,406} = 22.4$, $p = 0.001$, Fig. 7), saplings ($F_{6,406} = 19.6$, $p = 0.011$, Fig. 8), and seedlings ($F_{6,406} = 16.4$, $p = 0.021$, Fig. 9) significantly varied between the two sites, with lower densities in the disturbed site, especially for *Anogeissus leiocarpus*, *B. aegyptiaca*, and *Combretum hartmannianum* (Fig. 7, 8, and 9).

Table 3: Species Richness, Simpson's Evenness and Diversity Indices of Tree Species Identified in the Non-disturbed and Disturbed Sites of DBR in the Year 2020

Parameter	Non-disturbed site	Disturbed site	*T*	*P*
Species richness	35.0	17.0	18.6	< 0.001
Simpson's evenness index	0.51	0.42	28.2	0.053
Simpson's diversity index	17.6	7.20	33.2	< 0.001

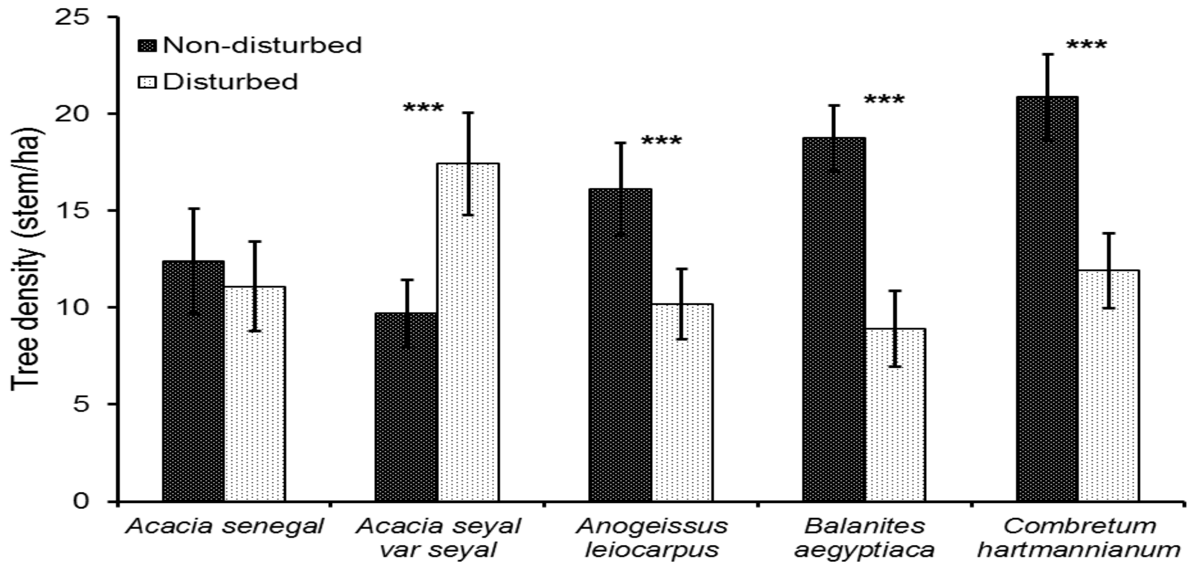

Figure 7: Mean Tree Density (stem/ha) of the Five Top Common Tree Species in the Non-disturbed and Disturbed Sites of DBR (2020). Asterisks above the bars show significant differences across the sites for each species according to Tukey's Post-Hoc tests (* = $p < 0.001$)**

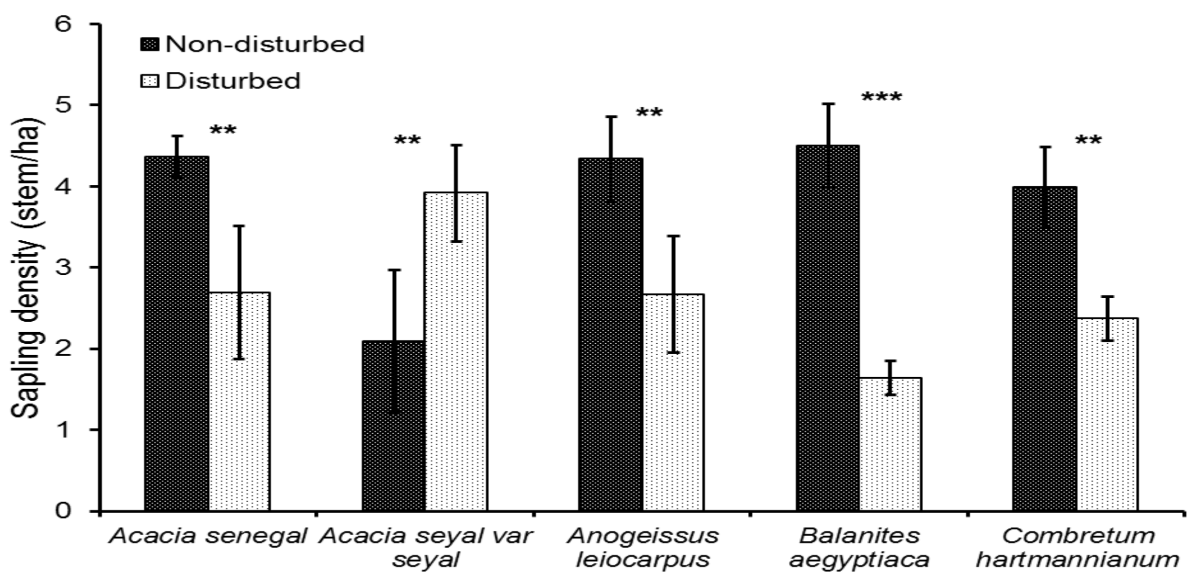

Figure 8: Mean Sapling Density (stem/ha) of the Five Top Common Tree Species in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve (2020). Asterisks above the bars show significant differences across the sites for each species according to Tukey's Post-Hoc tests (= $p < 0.01$; *** = $p < 0.001$)**

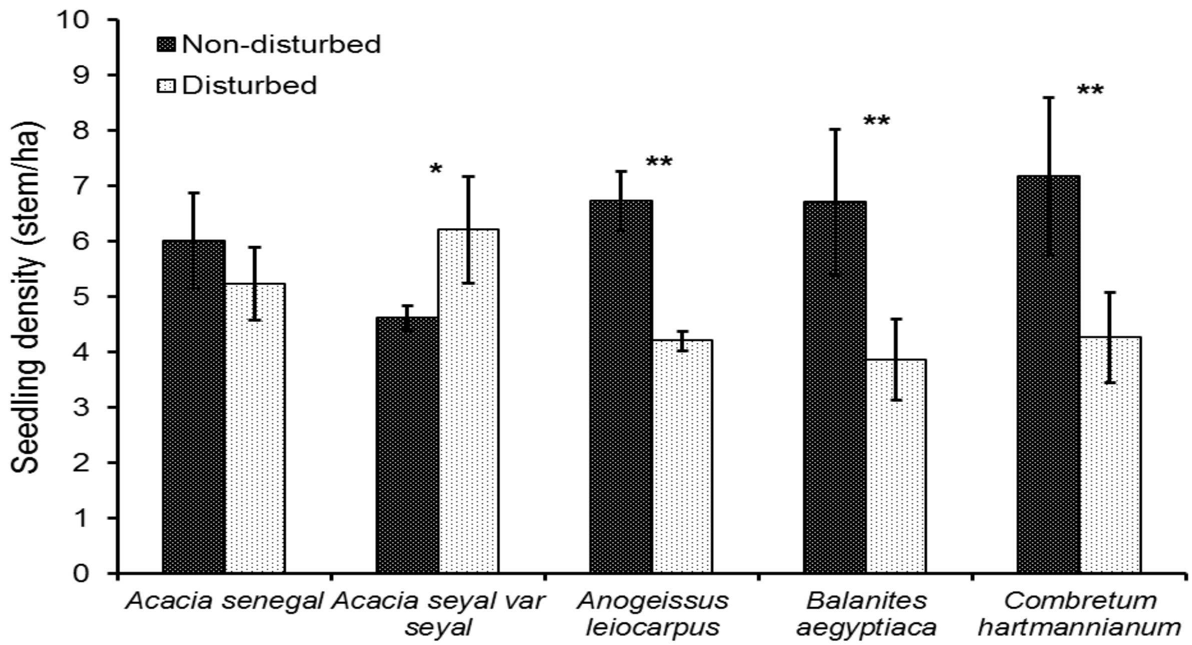

Figure 9: Mean Seedling Density (stem/ha) of the Five Top Common Tree Species in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve (2020). Asterisks above the bars show significant differences across the sites for each species according to Tukey's Post-Hoc tests (* = *p* < 0.05; ** = *p* < 0.01)

(ii) Low Dominance and Importance Value index (IVI) in Non-disturbed Site

Three tree species (*Acacia seyal var seyal*, *B. aegyptiaca*, and *C. hartmannianum*) are dominant in the two studied sites with an IVI of > 28 (Tables 4 and 5); however, *B. aegyptiaca* appeared as a top dominant tree species of the non-disturbed site ($F_{1,43}$ = 139.6, $p < 0.001$). Moreover, common tree species in the disturbed site exhibited significantly greater IVI values than non-disturbed sites ($F_{6,406}$ = 89.4, $p = 0.013$).

Further, the study findings showed that *A. senegal* and *A. seyal var seyal* have high relative frequency and significant relative abundance compared to all other tree species in the reserve as they demonstrated an inverse pattern ($F_{1,43}$ = 208.5, $p < 0.001$). The relative dominance of *A. seyal* at the disturbed site was four times that in non-disturbed ones, while its relative abundance is twice that of the non-disturbed site ($F_{1,43}$ = 167.4, $p < 0.011$, Tables 4 and 5).

Table 4: Total Number, Relative Abundance, Dominance, Frequency and IVI of the Tree Species Counted and Measured in Disturbed Site in Dinder Biosphere Reserve (2020)

No	Species	N	Relative Abundance (%)	Relative Dominance (%)	Relative Frequency (%)	IVI
1	*Acacia leata*	26	1.1	0.4	3.4	4.9
2	*Acacia mellifera*	56	2.2	1.2	3.7	7.1
3	*Acacia polyacantha*	35	1.3	0.9	2.0	4.1
4	*Acacia senegal*	146	7.6	6.6	7.6	21.8
5	*Acacia seyal var fistula*	65	2.4	1.9	3.9	8.2
6	*Acacia seyal var seyal*	517	27.9	37.2	14.3	79.4
7	*Adansonia digitata*	10	0.4	1.0	2.1	3.4
8	*Anogeissus leiocarpus*	98	3.9	3.9	2.8	10.7
9	*Balanites aegyptiaca*	189	10.2	13.4	12.8	36.4
10	*Combretum hartmannianum*	227	12.0	14.5	11.6	38.1
11	*Dichrostachys cinerea*	41	1.7	0.5	3.5	5.8
12	*Lannea fruticosa*	52	2.2	0.9	2.3	5.4
13	*Lonchocarpus laxiflorus*	171	9.4	3.6	6.7	19.4
14	*Sterculia setigera*	40	1.4	1.8	2.1	5.2
15	*Tamarindus indica*	12	0.7	0.6	2.1	3.4
16	*Terminalia brownii*	25	1.1	0.8	1.3	3.2
17	*Ziziphus spina-christi*	142	7.8	6.5	10.6	24.9

N = Total number of trees per site; IVI = Importance value index for each tree species per site.

Table 5: Total Number, Relative Abundance, Dominance, Frequency and IVI of the Tree Species Counted and Measured in Non-disturbed Site in Dinder Biosphere Reserve (2020)

No	Species	N	Relative Abundance (%)	Relative Dominance (%)	Relative Frequency (%)	IVI
1	*Acacia polyacantha*	54	2.2	0.8	2.0	5.0
2	*Acacia senegal*	161	5.5	4.1	3.3	12.9
3	*Acacia seyal var fistula*	27	1.1	0.4	1.1	2.6
4	*Acacia seyal var seyal*	319	10.9	9.1	8.4	28.4
5	*Anogeissus leiocarpus*	182	7.4	8.8	5.1	21.3
6	*Balanites aegyptiaca*	358	16.7	17.8	13.5	48.0
7	*Boscia senegalensis*	31	1.3	0.5	3.6	5.3
8	*Boswellia papyrifera*	96	2.5	3.5	3.0	9.0
9	*Combretum aculeatum*	30	1.2	0.5	3.6	5.2
10	*Combretum ghasalense*	67	2.7	2.7	2.6	7.9
11	*Combretum glutinosum*	87	3.5	3.5	4.0	11.0
12	*Combretum hartmannianum*	321	11.0	14.8	6.4	36.2
13	*Commiphora africana*	32	1.3	1.9	2.3	5.5
14	*Dalbergia melanoxylon*	45	1.8	1.2	2.6	5.5
15	*Dichrostachys cinerea*	31	1.3	0.5	4.0	5.8
16	*Diospyros mespiliformis*	44	1.8	1.6	2.0	5.4
17	*Gardenia lutea*	36	1.5	0.6	3.6	5.7
18	*Hyphaena thebiaca*	49	2.0	2.9	2.6	7.4
19	*Lannea fruticosa*	184	4.5	4.4	5.6	14.5
20	*Lannea nigritana*	91	3.7	3.4	3.7	10.8
21	*Lannea schimperi*	36	1.5	1.9	1.7	5.1
22	*Maerua angolensis*	30	1.5	0.6	2.8	5.3
23	*Piliostigma reticulatum*	20	0.8	0.6	1.1	2.6
24	*Pseudocedreca kotschyi*	58	2.4	2.7	3.4	8.5
25	*Pterocarpus lucens*	50	2.0	3.1	2.0	7.1
26	*Sclerocarya birrea*	48	2.0	2.6	2.3	6.8
27	*Sterculia setigera*	84	3.4	5.0	4.0	12.3
28	*Stereospermum kunthianum*	16	0.7	0.9	1.1	2.6
29	*Strychnos innocua*	28	1.1	0.7	3.6	5.4
30	*Tamarindus indica*	19	0.8	1.0	0.9	2.6
31	*Terminalia brownii*	14	0.6	0.7	0.6	1.9
32	*Terminalia macroptera*	52	2.1	3.1	2.3	7.5
33	*Xeromphis nilotica*	29	1.5	0.4	3.7	5.6
34	*Ximenia americana*	41	1.7	0.9	2.8	5.3
35	*Ziziphus spina-christi*	154	5.3	3.0	5.1	13.4

N = Total number of trees per site; IVI = Importance value index for each tree species per site

The outcomes of the principal component analysis for the importance value index (IVI) values surprisingly illustrated that the disturbed site host both the utmost and lowermost values of IVI. Based on the performed hierarchical cluster analysis (HCA) and the principal component analysis (PCA) of the IVI values, three groups have been clustered as; (High) tree species with highest IVI values, (Medium) tree species with medium values, while (Low) have low IVI values (Fig. 10). The common tree species in group (High) include *A. senegal*, *A. seyal*, *B. aegyptiaca*, *C. hartmannianum*, and *Ziziphus spina-christi* (Fig. 10). However, (Medium) and (Low) were dominated by *Anogeissus leiocarpus*, *A. polyacantha*, *Terminalia brownii*, *L. fruticosa*, *Dichrostachy cinerea*, *Sclerocarya birrea*, *Sterculia setigera*, *Tamarindus indica*, and *Adansonia digitata* (Fig. 10). The PCA had significantly explained the differences between the two sites by expressing 78% of their IVI variation.

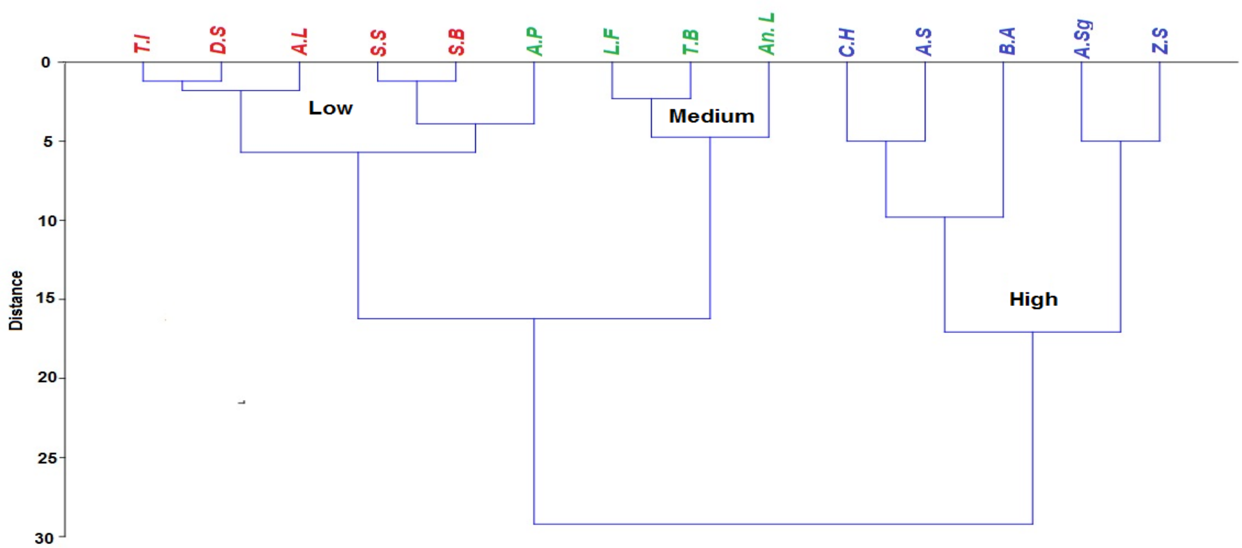

Figure 10: Dendrogram of the Clustered Common Tree Species at the Disturbed and Non-disturbed Sites in the Dinder Biosphere Reserve, Sudan which was ran in the hierarchical cluster analysis (HCA) based on the importance value index (IVI) values. (High) Tree species with highest IVI, i.e., A. S = *Acacia seyal var seyal*, C. H = *Combretum hartmannianum*, Z. S = *Ziziphus spina-christi*, B. A = *Balanites aegyptiaca*, A. Sg = *Acacia senegal*. (Medium) Tree species with intermediate IVI, i.e., An. L = *Anogeissus leiocarpus*, A. P = *Acacia polyacantha*, L. F = *Lannea fruticosa*, T. B = *Terminalia brownii*. (Low) Tree species with low IVI, i.e., D. C = *Dichrostachys cinerea*, T. I = *Tamarindus indica*, S.B = *Sclerocarya birrea*, and S. S = *Sterculia setigera*

(iii) Better Growth, Distribution, and Dendrometric Parameters in Non-disturbed Site

Non-disturbed site of DBR illustrated better growth and a strong natural regeneration with a juvenile population (seedlings and saplings) > 70 % of the total tree population in the site (Fig.

11). However, the disturbed site demonstrated an inverse trend with a higher percentage of adult trees (> 85%) to seedlings and saplings (< 15%) (Fig. 11). Moreover, the adult trees, saplings, and seedlings as growth forms and tree developmetal stages exhibited significant differences within the sites and across the study area in both disturbed and non-disturbed sites ($F_{2,48}$ = 118.6, p = 0.033 and $F_{2,48}$ = 164.4, p = 0.023, respectively; Fig. 11).

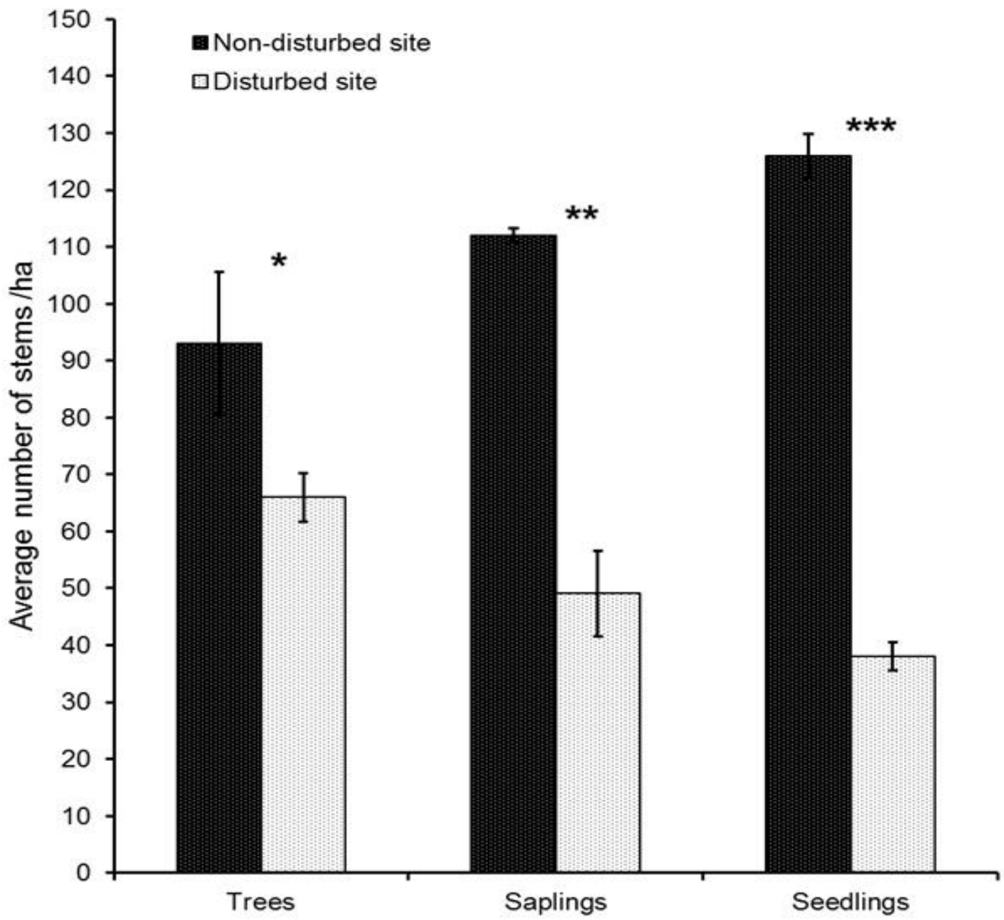

Figure 11: Mean Number of Stems of Adult Trees, Saplings, and Seedlings per ha Across all Tree Species Plotted along the Disturbed and Non-disturbed Sites. Asterisks above bars illustrate significant differences within the growth stages across the disturbed and non-disturbed sites according to Tukey's Post-Hoc tests (* = p < 0.05; ** = p < 0.01; *** = p < 0.001)

All dendrometric parameters of *B. aegyptiaca* tree species in the DBR shown significant differences between the disturbed and non-disturbed sites. The species density and tree crown widths in the non-disturbed site were double that of the disturbed site (Table 6). Moreover, the percent of *B. aegyptiaca* basal area contribution and distribution was intensively aggregated and regularly spreaded-out in the disturbed and non-disturbed sites, respectively (Blackman index, Table 6).

Table 6: Average (± SE) of the Dendrometric Parameters and Blackman Index of *B. aegyptiaca* Trees in Non-disturbed and Disturbed Sites at Dinder Biosphere Reserve collected (2020). DBH = Diameter at breast height (measured at 1.3 m above ground level)

Parameter	Non-disturbed site	Disturbed site	*T*	*P*
	Mean (± SE)	Mean (± SE)		
Tree DBH (cm)	33.8 ± 0.7	27.3 ± 0.4	2.3	0.036
Tree height (m)	12.7 ± 0.3	9.5 ± 0.2	3.7	0.001
Tree crown width (m)	7.9 ± 0.2	3.4 ± 0.1	3.4	0.002
Tree basal area (m^2 ha^{-1})	0.08 ± 0.03	0.06± 0.02	2.3	0.032
Tree volume (m^3)	0.39 ± 0.04	0.25 ± 0.1	2.9	0.004
Tree density (tree ha^{-1})	18.9 ± 0.4	8.9 ± 1.4	2.5	0.015
Basal area contribution (%)	9.5 ± 0.5	23.3 ± 1.2	30.7	0.001
Blackman index	0.51 ± 0.3	4.03 ± 0.4	39.4	0.001

4.1.2 Identifying the Sensitive Stage at which *B. aegyptiaca* is Most Affected by Livestock Browsing in Dinder Biosphere Reserve

(i) Seedling Survival, Mortality, Diameter, and Height

The study findings showed that the largest diameter, highest height and survival of *B. aegyptiaca* seedlings in the DBR, were found in the control site (CON) and under camel browsing (CAM) (Fig. 12, Tables 7 and 8). Seedling survivals have significantly differed across various browsed sites ($F_{3,196}$ = 46.36, $p < 0.001$; Fig. 12), the CON survivals were triple times greater than GOA survivals. Additionally, the seedlings mortality under goat browsing was twice that of CAT and four times that of CAM and CON, with significant differences between the four browsed sites ($F_{3,196}$ = 100.19, $p = 0.022$; Fig. 12).

Furthermore, the seedling height illustrated a significant difference within the studied sites between the browsed (affected) and unbrowsed (healthy) seedlings, especially in the GOA site (T = 115.3, $p = 0.001$; Table 8). The similar pattern was observed for the seedling diameter (T = 152.9, $p = 0.001$; Table 7). Besides that, the correlation between the seedling density and its height in all studied sites displayed a concrete negative relationship, with the greatest coefficient of determination value (R^2) in the control site ($R^2 = 0.81$, $\beta = -6.3$, $p = 0.032$, Fig. 13).

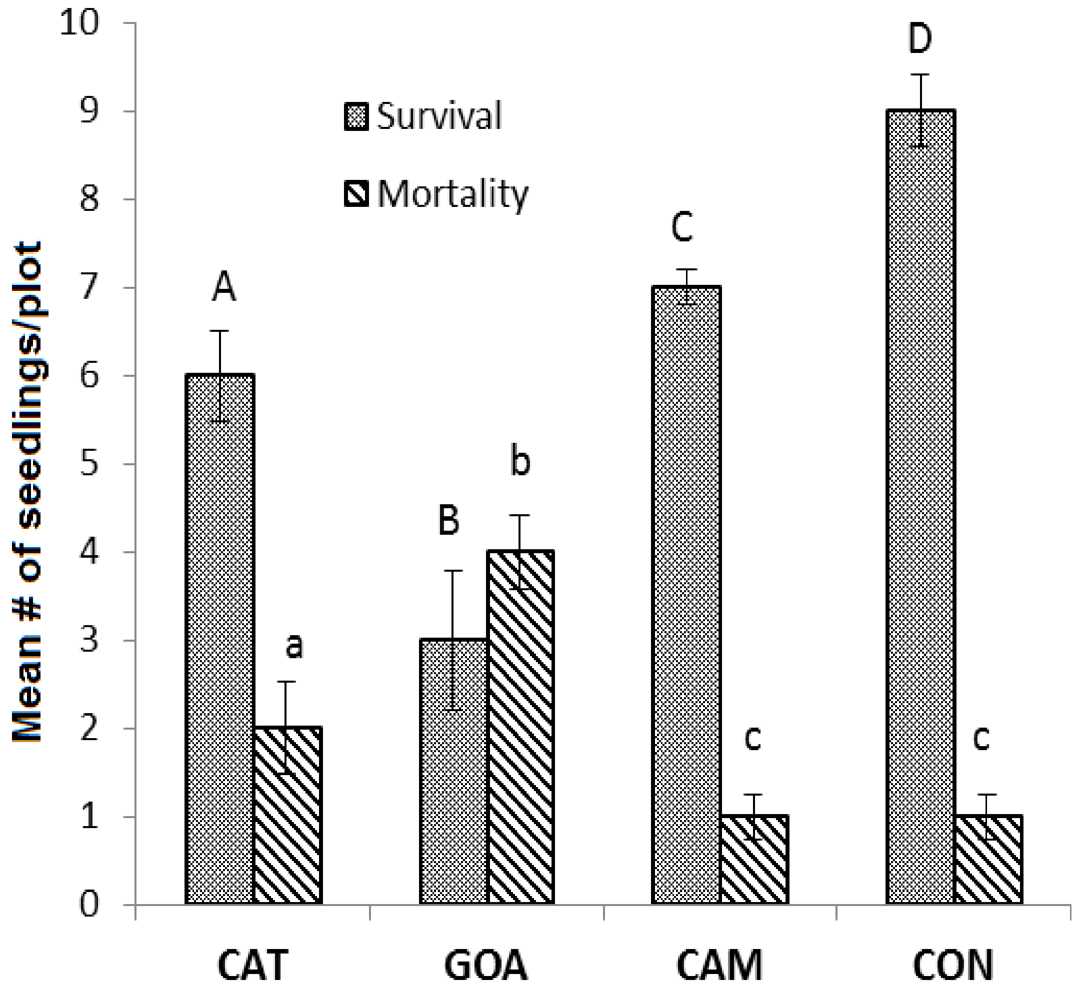

Figure 12: Mean Number of *B. aegyptiaca* Seedling Survival and Mortality Plotted along the Four Studied Sites with Different Browsing Species: CAT = Site browsed predominantly by cattle, GOA = Site browsed predominantly by goat, CAM = Site browsed predominantly by camel and CON = Control without livestock browsers. Different letters above bars indicate significant differences across the sites according to Tukey's Post-Hoc test (p < 0.05). Capital letters testing for survival, and small letters show the test for mortality

Table 7: Mean Stem Diameter (cm) of Browsed (affected) and Unbrowsed (healthy) *B. aegyptiaca* Seedlings Across Different Browsing Sites in Dinder Biosphere Reserve (2020). N = total number of seedlings/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

Sites	Healthy		Affected		*T*	*P*
	N	Mean (±SE)	N	Mean (±SE)		
GOA	46	2.0 ± 0.03	114	1.2 ± 0.02	152.9	0.001
CAT	208	2.2 ± 0.04	97	1.6 ± 0.03	90.5	0.003
CAM	292	2.6 ± 0.02	59	2.1 ± 0.03	132.2	0.026
CON	423	2.7 ± 0.01	26	2.3 ± 0.08	94.4	0.044

Table 8: Mean Total Height (m) of Browsed (affected) and Unbrowsed (healthy) *B. aegyptiaca* Seedlings Across Different Browsing Sites in Dinder Biosphere Reserve (2020). N = total number of seedlings/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

Sites	Healthy		Affected		*T*	*P*
	N	Mean (±SE)	N	Mean (±SE)		
GOA	46	1.02 ± 0.09	114	0.32 ± 0.07	112.3	0.001
CAT	208	1.15 ± 0.01	97	0.41 ± 0.06	64.7	0.001
CAM	292	1.24 ± 0.04	59	0.63 ± 0.08	77.2	0.023
CON	423	1.41 ± 0.03	26	0.78 ± 0.02	76.9	0.034

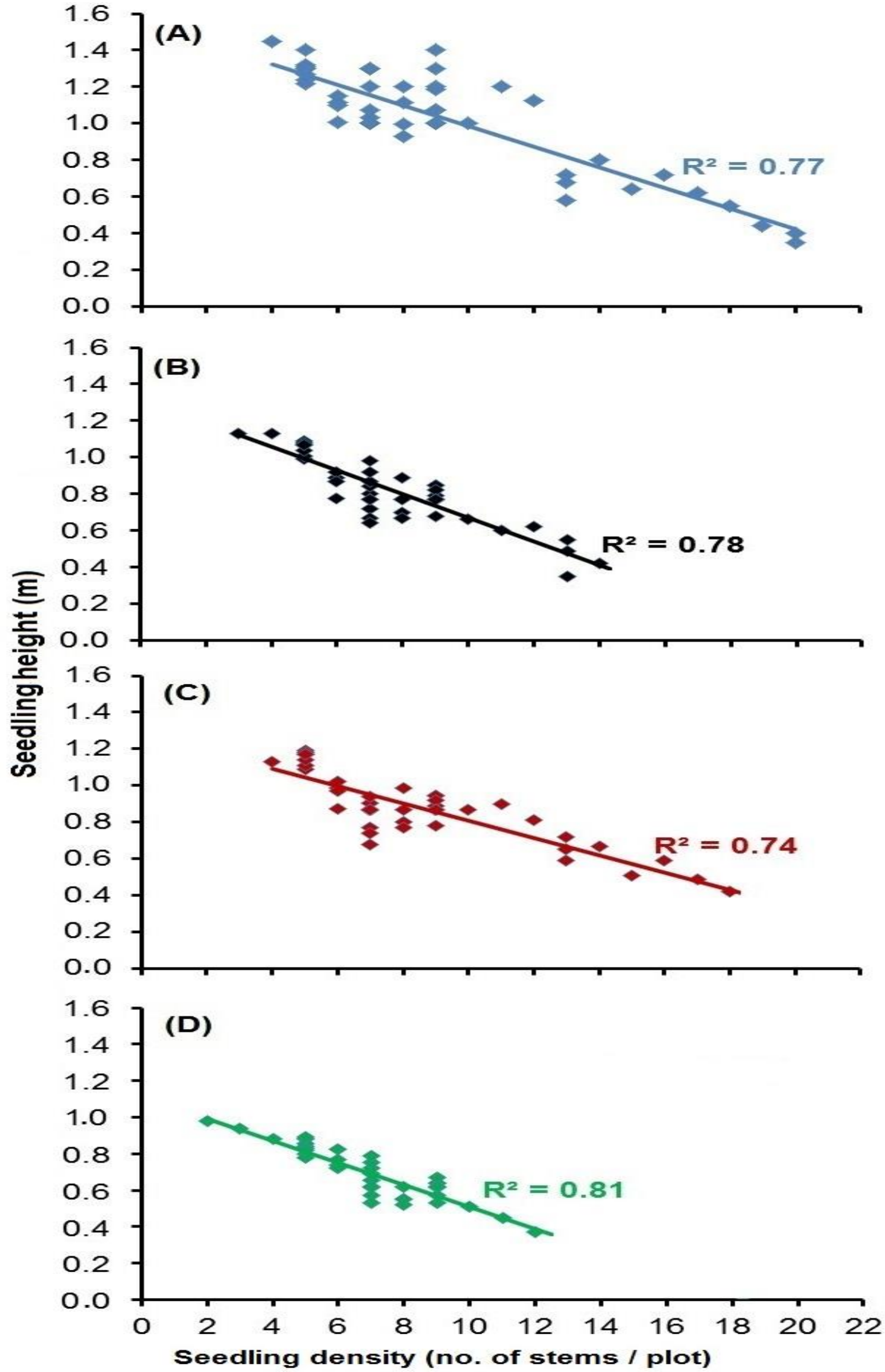

Figure 13: Correlation Between the Height of *B. aegyptiaca* Seedlings and the Sample plot Seedling Density in the Differently Browsed Sites of the Dinder Biosphere Reserve (2020). (A) = GOA (Site browsed predominantly by goat), (B) = CAM (Site browsed predominantly by camel), (C) = CAT (Site browsed predominantly by cattle), and (D) = CON (control without livestock browsers)

(ii) Sapling Survival, Mortality, Diameter, and Height

The sapling survival was slightly different among the sites ($F_{3,196} = 12.42$, $p = 0.055$), with few survivals under camel and goat browsing compared to the cattle browsing and control site (Fig. 14). In contrast, sapling mortality exhibited significant variation between the sites ($F_{3,196} = 76.4$, $p < 0.001$), where mortality in GOA was three times higher than that of CAT and CON (Fig. 14).

The highest sapling height was found in the GOA and the largest diameter in the CON (Tables 9 and 10). Healthy saplings in GOA have a height four times higher than affected ones ($T = 84.3$, $p < 0.001$, Table 9), and their diameter is also double that of affected saplings ($T = 144.2$, $p < 0.001$, Table 10). Besides that, the regression correlation between the sapling density and its height demonstrated a strong negative correlation throughout the studied sites with high coefficient of determination values under camel browsing and control site ($R^2 = 0.86$, $\beta = -25.8$, $p < 0.001$; $R^2 = 0.86$, $\beta = -27.6$, $p < 0.001$, Fig. 15).

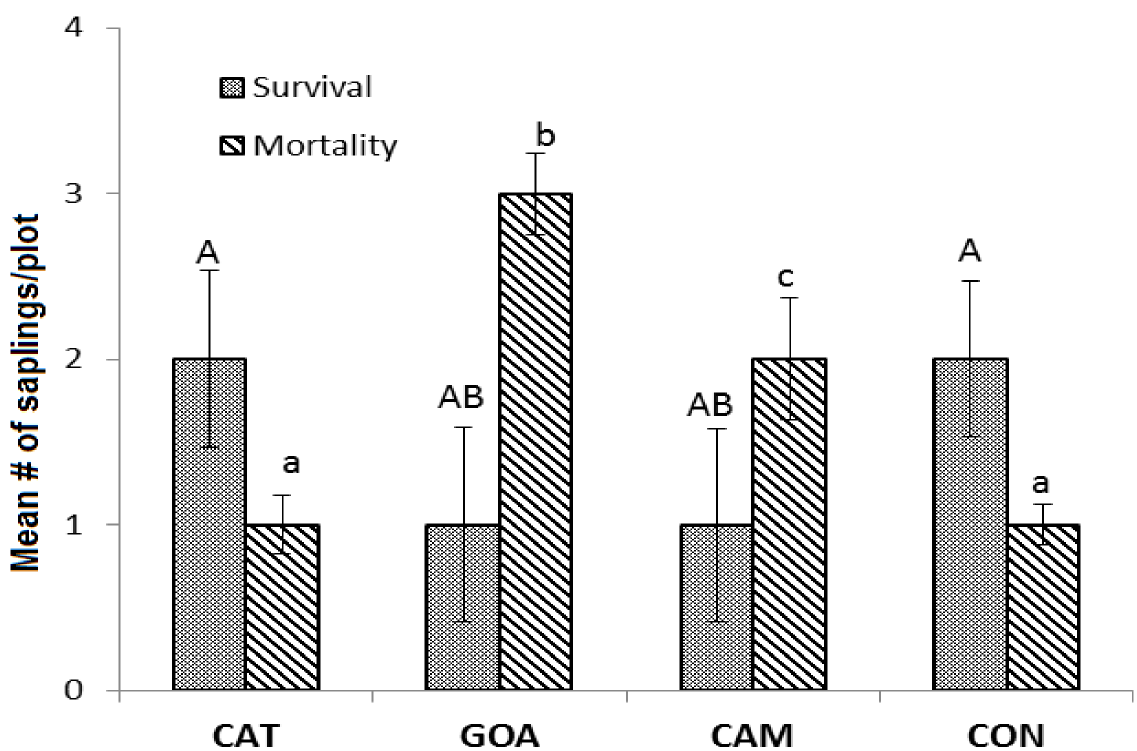

Figure 14: Mean Number of *B. aegyptiaca* Sapling Survival and Mortality Plotted along the Four Studied Sites with Different Browsing Species: CAT = Site browsed predominantly by cattle, GOA = Site browsed predominantly by goat, CAM = Site browsed predominantly by camel and CON = Control without livestock browsers. Different letters above bars indicate significant differences across the sites according to Tukey's Post-Hoc test (*p* < 0.05). Capital letters testing for survival, and small letters show the test for mortality

Table 9: Mean Total Height (m) of Browsed (affected) and Unbrowsed (healthy) *B. aegyptiaca* Saplings Across Different Browsing Sites in DBR (2020). N = total number of saplings 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

Sites	Healthy		Affected		*T*	*P*
	N	Mean (±SE)	N	Mean (±SE)		
GOA	29	2.32 ± 0.06	72	0.56 ± 0.03	82.3	< 0.001
CAT	146	1.91 ± 0.02	54	0.84 ± 0.04	67.6	< 0.001
CAM	35	2.45 ± 0.02	66	1.21 ± 0.07	87.9	< 0.001
CON	181	1.86 ± 0.01	19	0.92 ± 0.03	85.7	< 0.001

Table 10: Mean Stem Diameter (cm) of Browsed (affected) and Unbrowsed (healthy) *B. aegyptiaca* Saplings Across Different Browsing Sites in Dinder Biosphere Reserve (2020). N = total number of saplings 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

Sites	Healthy		Affected		*T*	*P*
	N	Mean (±SE)	N	Mean (±SE)		
GOA	29	6.3 ± 0.06	72	3.1 ± 0.03	146.2	< 0.001
CAT	146	6.4 ± 0.02	54	3.8 ± 0.04	235.5	0.001
CAM	35	6.6 ± 0.02	66	4.3 ± 0.07	115.7	0.021
CON	181	6.7 ± 0.01	19	5.8 ± 0.03	109.6	0.032

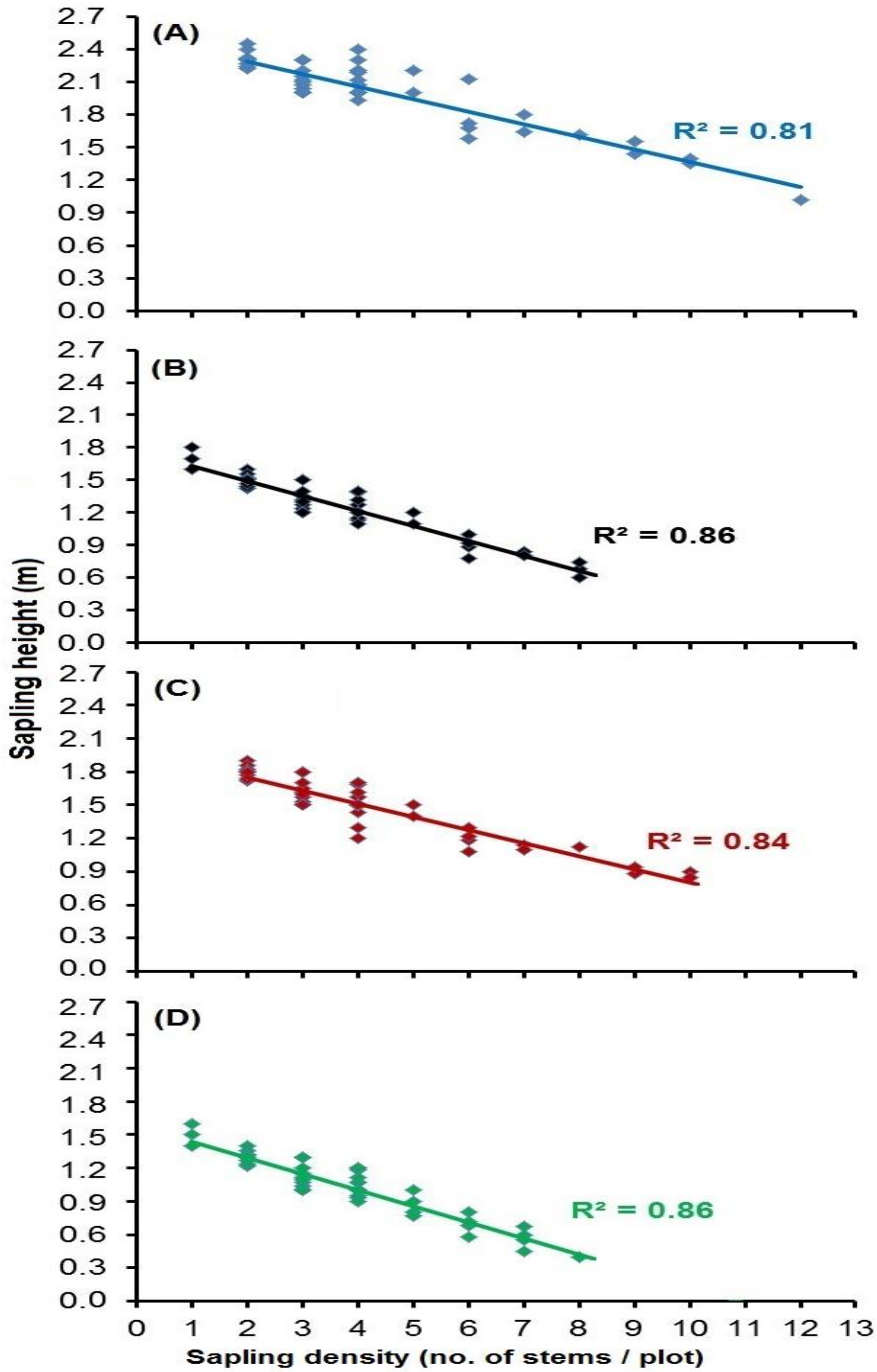

Figure 15: Correlation Between the Height of *B. aegyptiaca* Saplings and the Sample plot Saplings Density in the Different Browsed Sites of the Dinder Biosphere Reserve (2020). (A) = GOA (Site browsed predominantly by goat), (B) = CAM (Site browsed predominantly by camel), (C) = CAT (Site browsed predominantly by cattle), and (D) = CON (control without livestock browsers)

(iii) Saplings Recovered Less than Seedlings Under Cattle and Camel Browsing

Although the mean recovered seedlings and saplings of *B. aegyptiaca* differed significantly across the four browsed sites, recovered seedlings in CAT and CAM were double the recovered saplings in the same sites ($F_{3,196}$ = 17.27, p < 0.001 and $F_{3,196}$ = 6.76, p < 0.001, respectively, Fig. 16). Moreover, the study observed a limited number of recovered seedlings and saplings under goat and camel browsing compared to the considerable numbers of recovered ones under cattle browsing (Fig. 16).

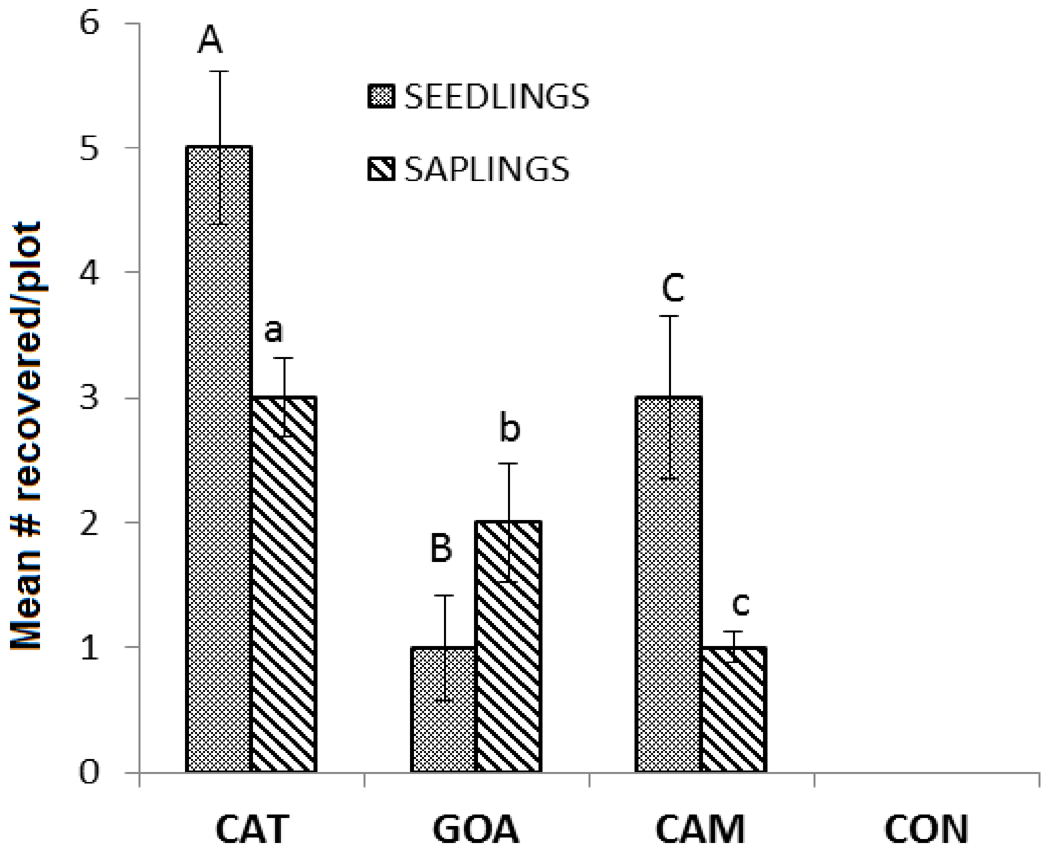

Figure 16: Mean Number of *B. aegyptiaca* Seedlings and Saplings Recovered after been Browsed Across the Four Studied Sites with Different Browsing Species: CAT = Site browsed predominantly by cattle, GOA = Site browsed predominantly by goat, CAM = Site browsed predominantly by camel, and CON = Control without livestock browsers. Different letters above bars indicate significant differences across the sites according to Tukey's Post-Hoc test (p < 0.05). Capital letters testing for seedlings, and small letters show the test for saplings

4.1.3 Assessing the Effect of Illegal Cutting of *B. aegyptiaca* Branches on Tree Survival, Fruit Production, and Seedling Recruitment in Dinder Biosphere Reserve

(i) Largest Crown Width, Height, and Most Fruiting Branches in Non-disturbed Site

The average number of fruiting branches of *B. aegyptiaca* and other tree species were three and two times higher in the non-disturbed site than that in the disturbed site, respectively, with significant differences within the site across tree species ($F_{1,98}$ = 112, p = 0.011) and across the sites ($F_{1,98}$ = 139, $p < 0.001$, Fig. 17). The number of *B. aegyptiaca* fruiting branches was by about 30% higher in non-disturbed sites but significantly lower in disturbed sites compared to the other tree species (Fig. 17). The correlation between the fruiting branches and crown width of *B. aegyptiaca* and other tree species in both sites illustrated strong positive relationships (β = 17.1, p = 0.01; β = 28.2, p = 0.02, respectively, Fig. 18).

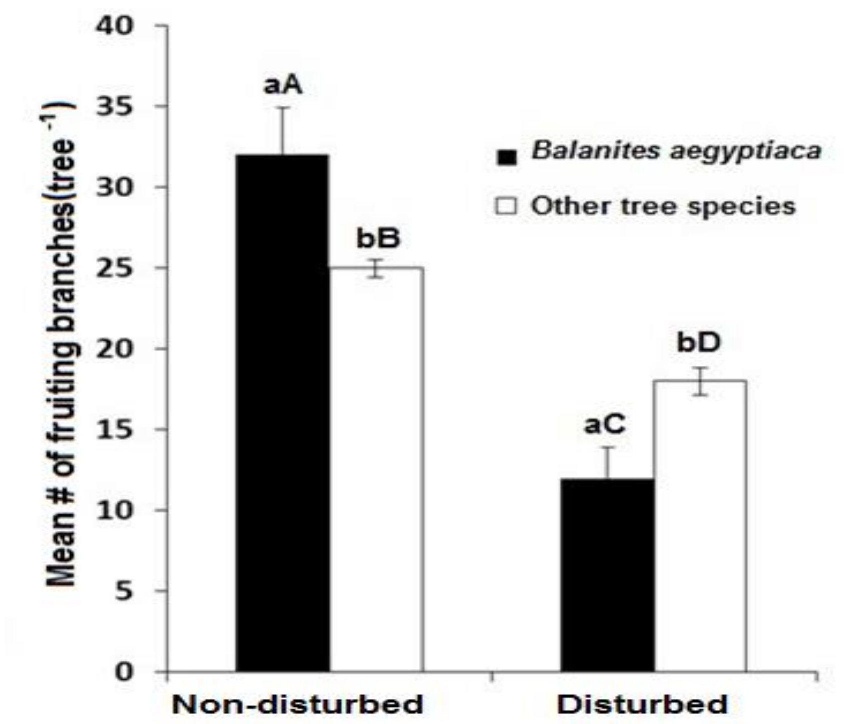

Figure 17: Average (± SE) Number of Fruiting Branches of *B. aegyptiaca* and Other Tree Species Sampled in the Disturbed and Non-disturbed Sites of the Dinder Biosphere Reserve (2020 – 2021). Various letters above bars show significant differences within the sites (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc test with $p < 0.05$

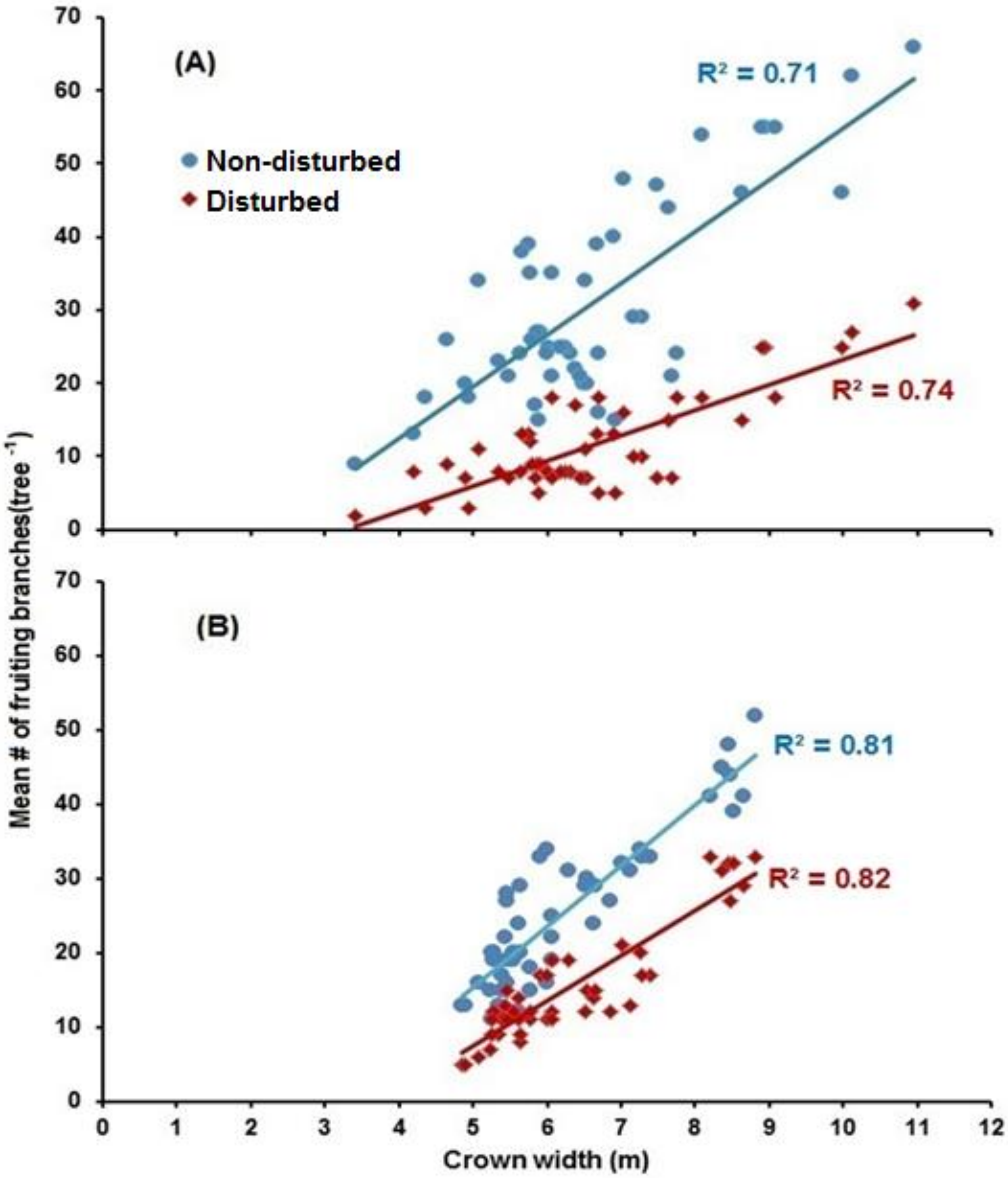

Figure 18: Correlation Between Crown Width and Fruiting Branches for (A) *B. aegyptiaca* and (B) Other Tree Species in the Non-disturbed and Disturbed Sites at Dinder Biosphere Reserve (2020 – 2021)

The non-disturbed site showed the highest values of diameter at breast height (DBH), total tree height (H), and crown width (CW), with significant differences within the site between the tree species, and across the sites ($F_{1,196}$ = 29.8, p = 0.002; $F_{1,196}$ = 80, p < 0.001; $F_{1,196}$ = 94.8, p < 0.001, Fig. 19). The values of H and CW of *B. aegyptiaca* in the non-disturbed site were double that of the disturbed site (T = 52.3, p < 0.001; T = 37.4, p = 0.001, Fig. 19).

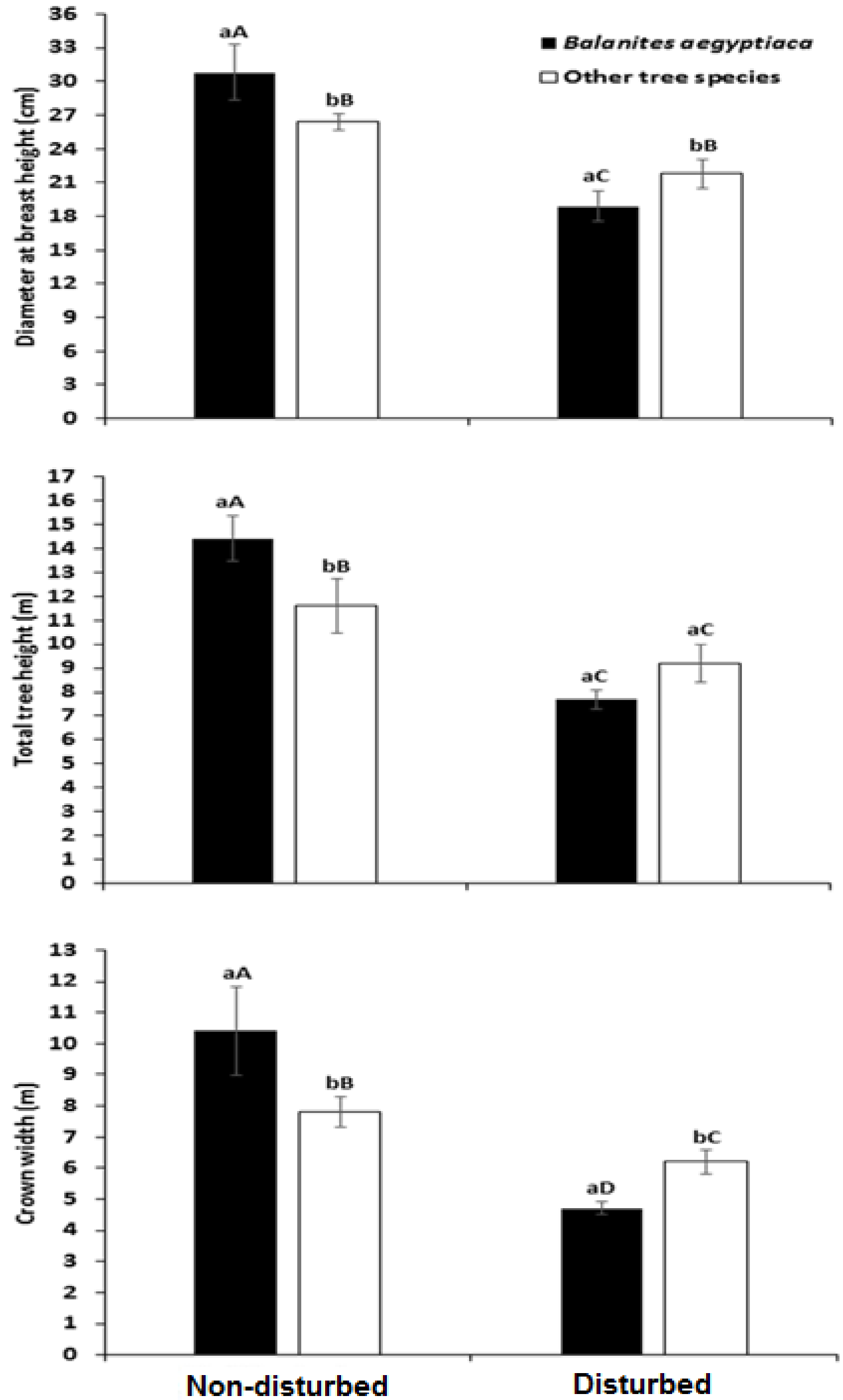

Figure 19: **Average (±SE) Tree Diameter at Breast Height, Tree Height, and Crown Width of *B. aegyptiaca* and Other Tree Species in Non-disturbed and Disturbed Sites of the Dinder Biosphere Reserve Measured (2020 – 2021). Various letters above bars signpost significant differences within the sites (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc test ($p < 0.05$)**

(ii) Lowest Seedling, Sapling, and Tree Density in the Disturbed Site

The density of the mature trees, saplings, and seedlings of *B. aegyptiaca* and other tree species varied significantly across sites, with saplings and mature trees of *B. aegyptiaca* at the non-disturbed site being three times and double that of the disturbed site ($F_{1,196} = 94.5$, $p < 0.001$; $F_{1,196} = 23.7$, $p < 0.001$, respectively). Other tree species saplings were twice as many in the non-disturbed as in the disturbed site ($F_{1,196} = 63.7$, $p = 0.001$, Fig. 20). Seedlings showed similar significant differences between sites ($F_{1,196} = 100.8$, $p < 0.001$, Fig. 20).

Further, the correlation between the tree density and the average number of fruiting branches showed a strong negative relationship for both *B. aegyptiaca* ($\beta = - 0.36$, $p = 0.002$; $\beta = - 0.58$, $p = 0.001$) and other tree species ($\beta = - 0.42$, $p < 0.001$; $\beta = - 0.65$, $p = < 0.001$) in the non-disturbed and disturbed sites, respectively (Fig. 21). While, the density of saplings ($\beta = 0.45$, $p < 0.001$; $\beta = 0.33$, $p < 0.001$) and seedlings ($\beta = 0.83$, $p < 0.001$; $\beta = 0.78$, $p < 0.001$) were positively related with the average number of fruiting branches in the non-disturbed and disturbed sites, respectively (Fig. 21).

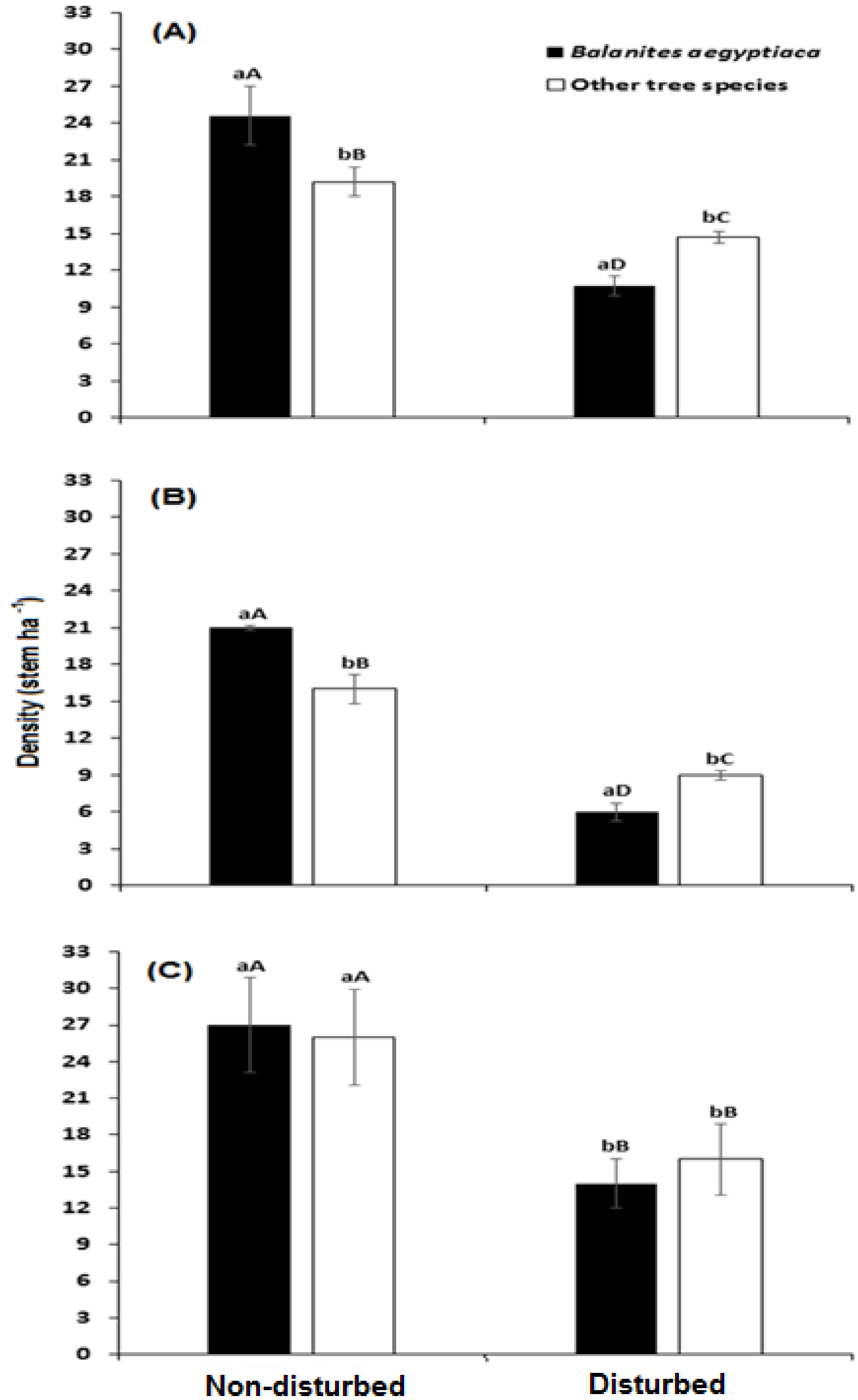

Figure 20: **Average (±SE) Density of *B. aegyptiaca* and Other Tree Species in the Non-disturbed and Disturbed Sites of the Dinder Biosphere Reserve (2020 – 2021). (A) = Mature trees, (B) = Saplings, and (C) = Seedlings. Various letters above bars signpost significant differences within the sites (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc test (p < 0.05)**

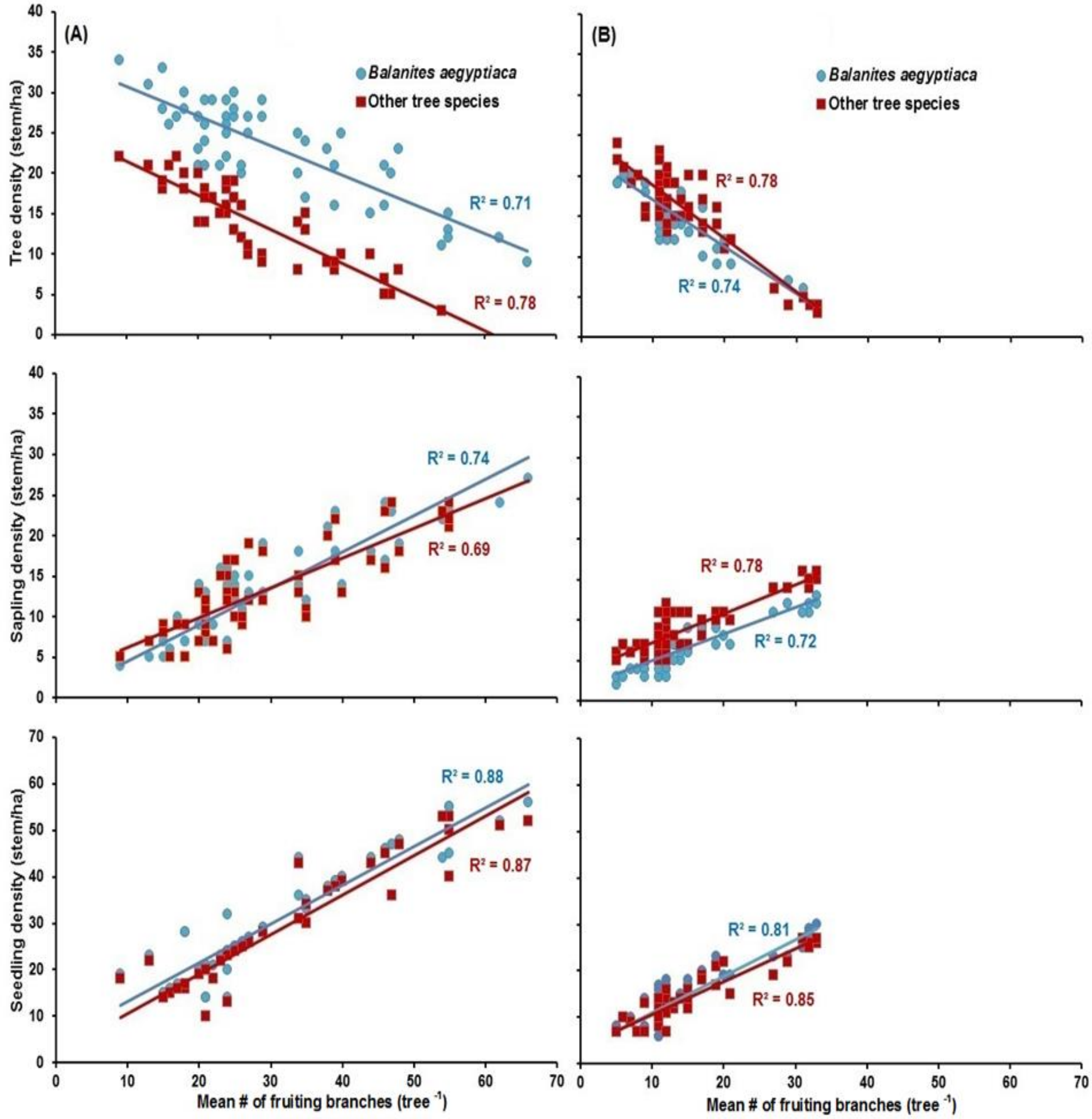

Figure 21: **Correlation Between the Density of Adult Trees, Saplings, and Seedlings, and Fruiting Branches for *B. aegyptiaca* and Other Tree Species in (A) the Non-disturbed and (B) Disturbed sites at Dinder Biosphere Reserve (2020 – 2021)**

4.1.4 Quantifying the Differences in the Soil Chemical Properties Beneath the Affected and Healthy Trees in Dinder Biosphere Reserve

The N and P beneath tree canopies in the non-disturbed site were almost double that of the disturbed site, with higher contents under other tree species compared to *B. aegyptiaca* ($F_{1,\ 196}$ = 68.1, $p < 0.001$; $F_{1,\ 196}$ = 97.9, $p < 0.001$, Fig. 22, A and E). Moreover, SOC and the C/N ratio exhibited a similar trend with significant differences within and between the sites, with lower quantities under other tree species than *B. aegyptiaca* ($F_{1,\ 196}$ = 49.2, $p < 0.001$; $F_{1,\ 196}$ = 75.5, p = 0.012, respectively, Fig. 22, B and F).

The soil underneath trees in disturbed site showed twice as high Na and ECe compared to the non-disturbed sites ($F_{1, 196}$ = 535.8, $p < 0.001$; $F_{1, 196}$ = 16.1, $p < 0.001$, respectively, Fig. 22, D and H), while soil K showed no significant differences within the sites between *B. aegyptiaca* trees and other tree species, but was significant between sites ($F_{1, 196}$ = 5.4, $p = 0.464$; $F_{1, 196}$ = 43.5, $p < 0.001$, respectively, Fig. 22, C). Soil pH displayed the same pattern as K ($F_{1, 196}$ = 59.3 and $p = 0.041$, Fig. 22, G).

Furthermore, there was a strongly positive correlation between the N, SOC, K, P, and the crown width of adult *B. aegyptiaca* trees ($R^2 = 0.76$, $p < 0.001$; $R^2 = 0.74$, $p < 0.001$; $R^2 = 0.75$, $p < 0.001$; $R^2 = 0.85$, $p < 0.001$, respectively), while for Na and the C/N ratio was negative ($R^2 = 0.71$, $p = 0.011$; $R^2 = 0.73$, $p = 0.001$, respectively), (Fig. 23).

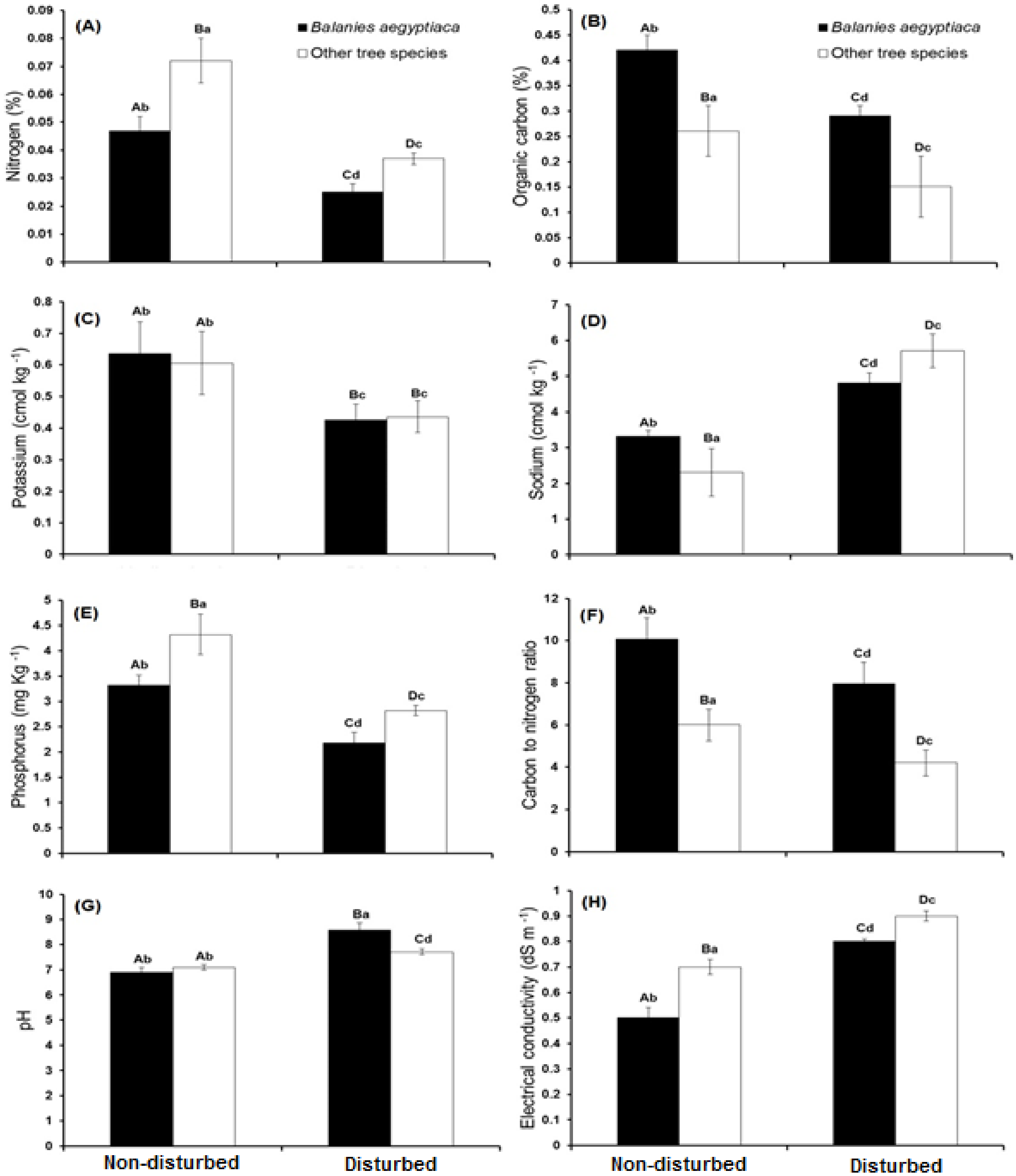

Figure 22: **Average (±SE) (A) Nitrogen, (B) Organic Carbon, (C) Potassium, (D) Sodium, (E) Phosphorus, (F) Carbon to Nitrogen Ratio, (G) pH, and (H) Electrical Conductivity of *B. aegyptiaca* and Other Tree Species in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve (2020 – 2021). Various letters above bars signpost significant differences within the sites (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc test ($p < 0.05$)**

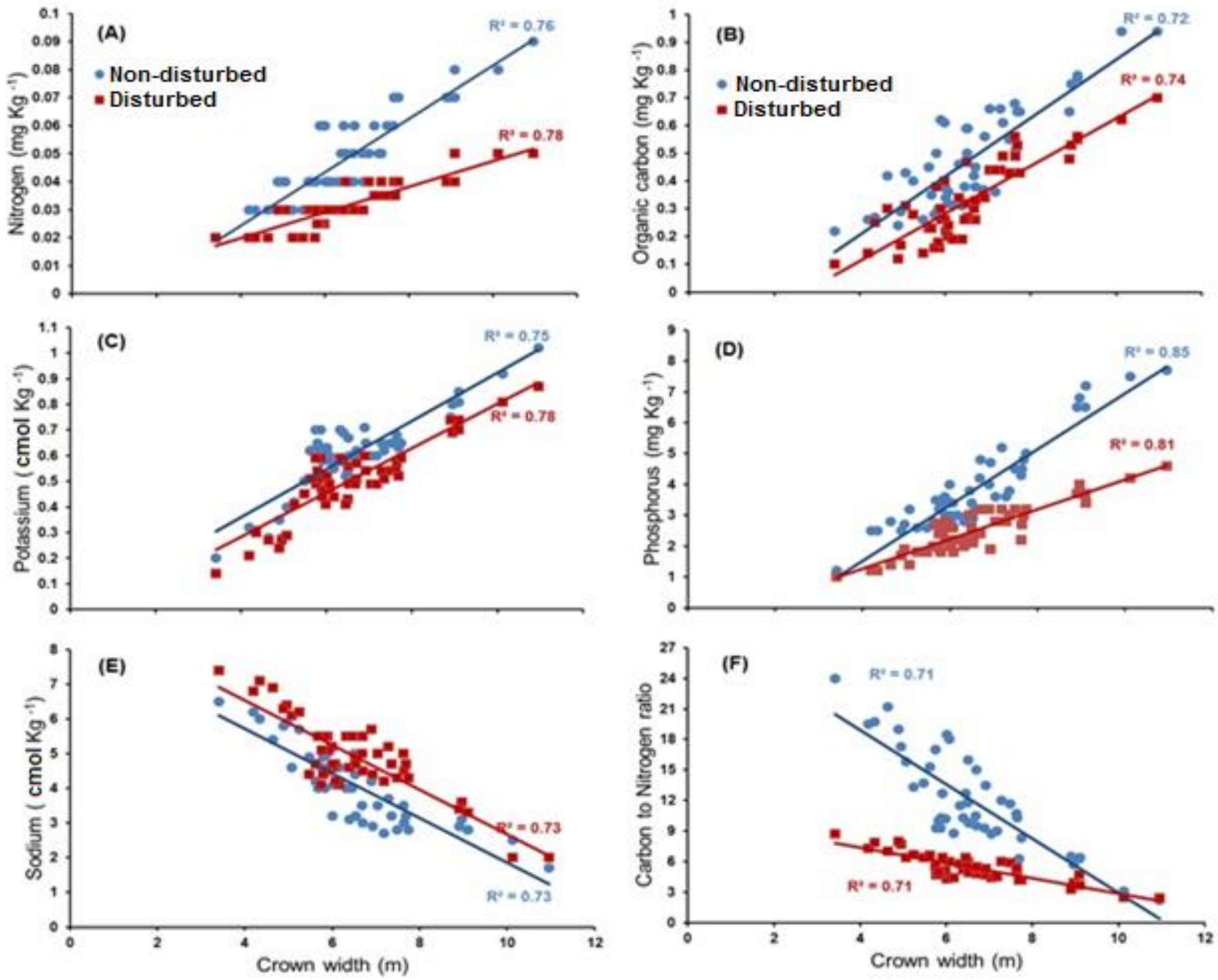

Figure 23: Correlation Between the Crown Width of the Adult Trees of *B. aegyptiaca* and the (A) Soil Nitrogen, (B) Organic Carbon, (C) Potassium, (D) Phosphorus, (E) Sodium, and (F) Carbon to Nitrogen Ratio, in the Non-disturbed and Disturbed Sites of Dinder Biosphere Reserve (2020 – 2021)

4.1.5 Evaluating the Influence of *B. aegyptiaca* Population Decline on the Income of Local People within and Around Dinder Biosphere Reserve

(i) Socio-Demographic Characteristics of the Study Participants

The socio-demographic findings of the study indicated that 54% and 46% of the study participants were female and male, respectively, and 40% of them were in the age group (21 – 30) (Fig. 24 A and C). The majority of the participants were Non-timber forest products (NTFPs) collectors (30%) and Agro-pastoralists (22%), with their highest education as secondary (35%) and primary school (30%) (Fig. 24 B and D).

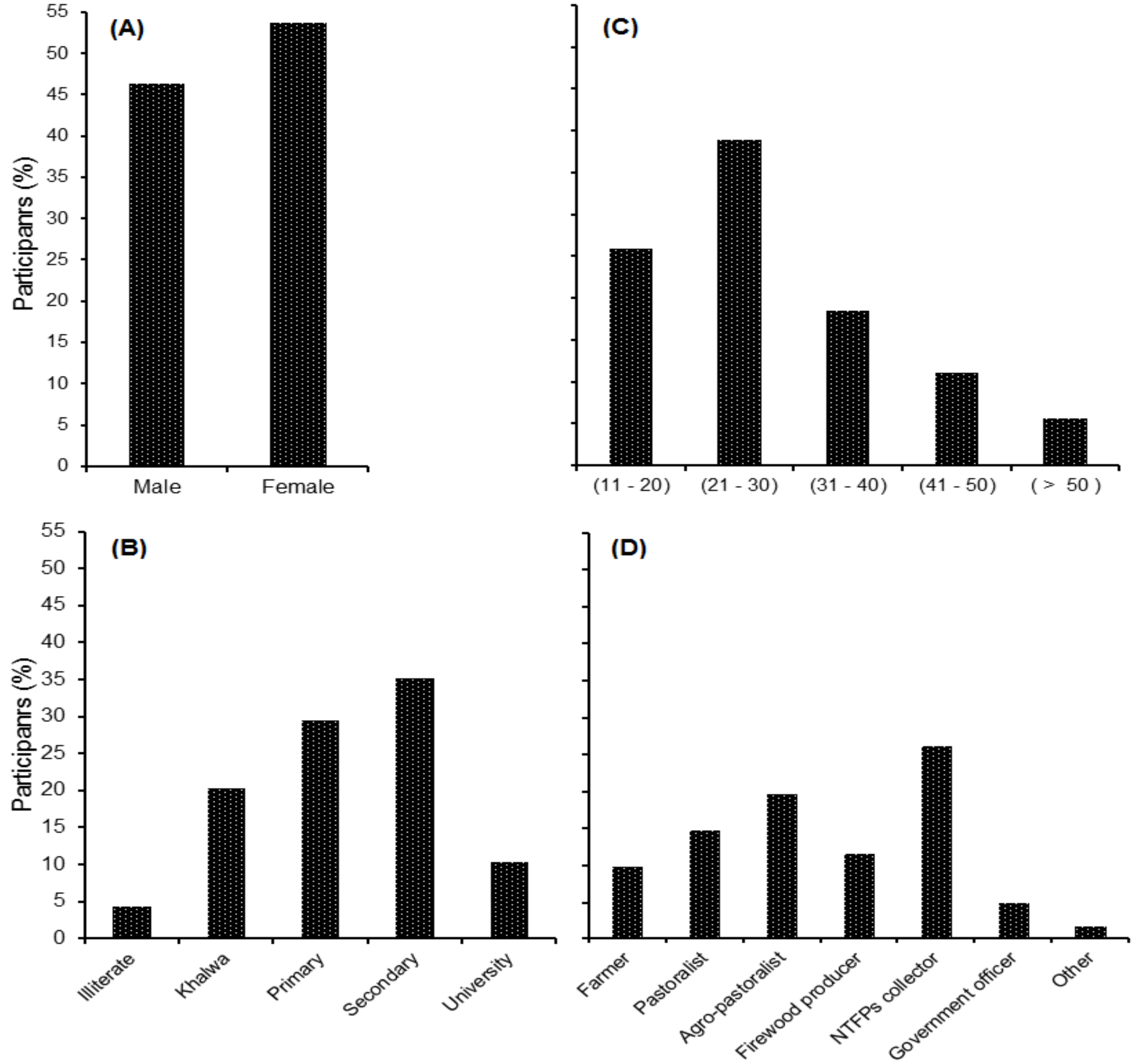

Figure 24: The Socio-demographic Characteristics of the Study Participants. (A) Gender, (B) Level of Education, (C) Age Group, and (D) Occupation of the Participant. Khalwa is an Islamic School where Students are learning Quran and the Islamic Sciences

(ii) The Ten Top most Utilized Tree Species for Food, Medicine, Fodder, and Building

Food, feed, medicine, building materials, and fuelwood are among the vital needs of forest-based communities. The study found that *B. aegyptiaca* was the most frequently used tree species for medicine (32%), food (27%), and feed (26%), while *Anogeissus leiocarpus* (26%), *Ziziphus spina-christi* (17%), and *Combretum hartmannianum* (15%) were species preferred by the locals for building purposes (Fig. 25).

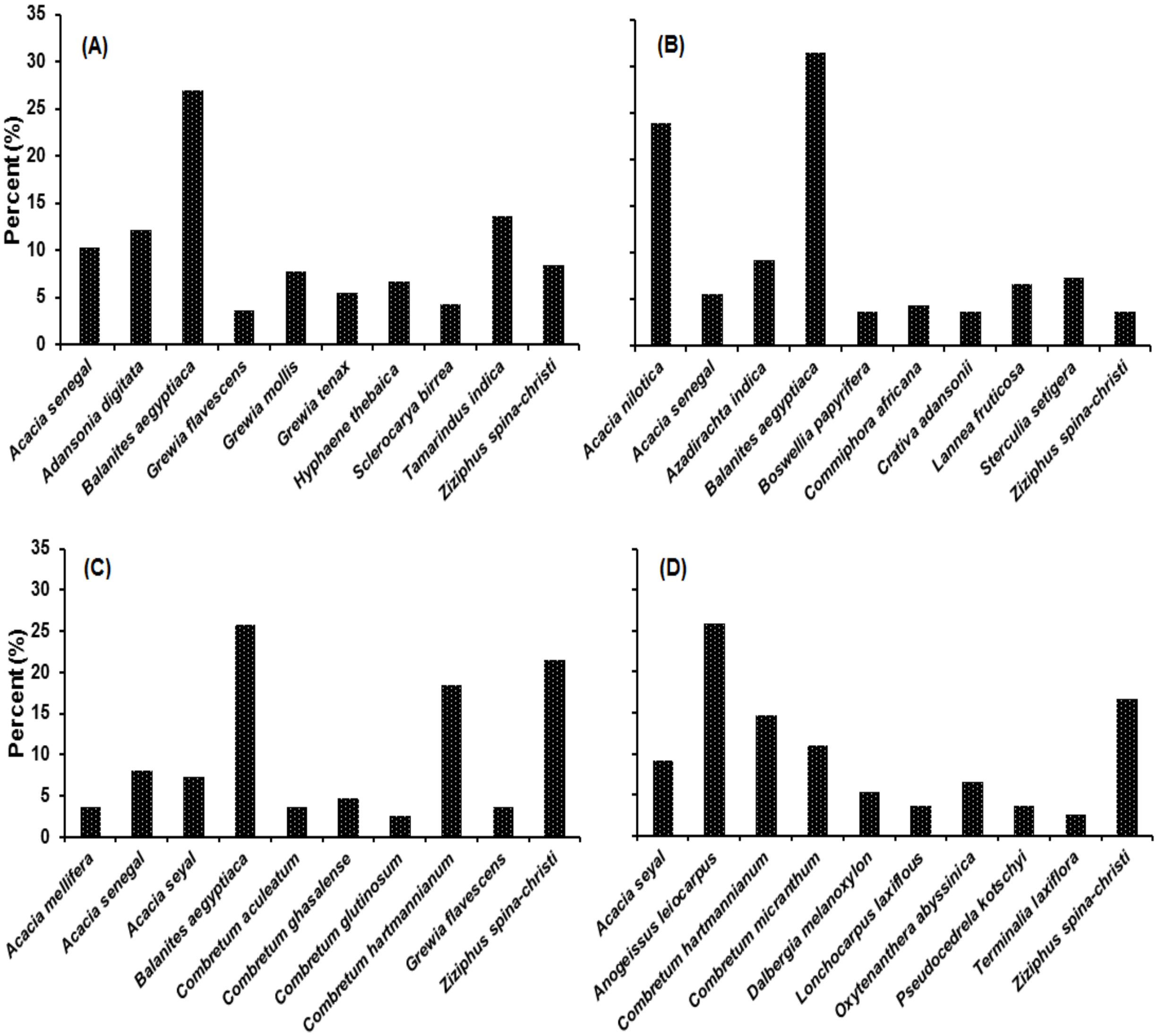

Figure 25: **The Ten Most Commonly Utilized Tree Species by the Locals for (A) Food, (B) Medicine, (C) Fodder, and (D) Building Materials According to the Current Study Survey Conducted at Dinder Biosphere Reserve in the Year 2021, N = 270**

Furthermore, among the collectors, sellers, and users of *B. aegyptiaca* tree products, 52% of the respondents confirmed that they collected the fruits, and 20% and 14% as leaves and roots, respectively (Fig. 26). While 41% of the collected products usually gathered by children, most of the selling activities (52%) and the revenue management (54%) are performed by women.

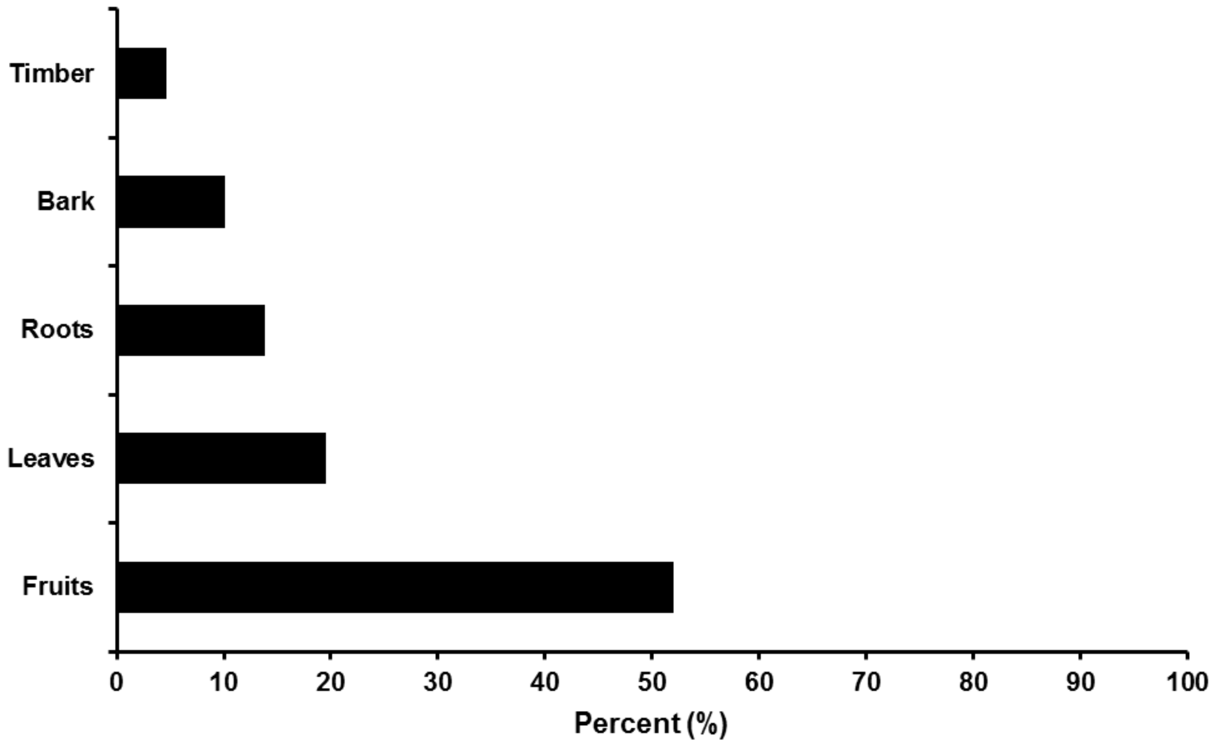

Figure 26: The Common Parts of *B. aegyptiaca* Tree Species that have been Collected, Sold, or Used by the Study Participants, According to the Current Study Survey Conducted at Dinder Biosphere Reserve in the Year 2021, N = 270

(iii) Better Revenue and Markets in Town

The study found that the town markets (> 40%) were more attractive to the NTFPs collectors and traders than a village (30%), locality (20%), and district (9%) (Fig. 27). Moreover, the collected amounts of *B. aegyptiaca* fruits (kg $^{-1}$ month) were significantly different between the seasons across the surveyed villages (Fig. 28). This variation is unambiguous for Elkhairat ($F_{1,268}$ = 92, p = 0.013), Gari ($F_{1,268}$ = 78.5, p = 0.021), Gadaf ($F_{1,268}$ = 137.8, p = 0.001), and Mokla ($F_{1,268}$ = 102.4, p = 0.015) (Fig. 28).

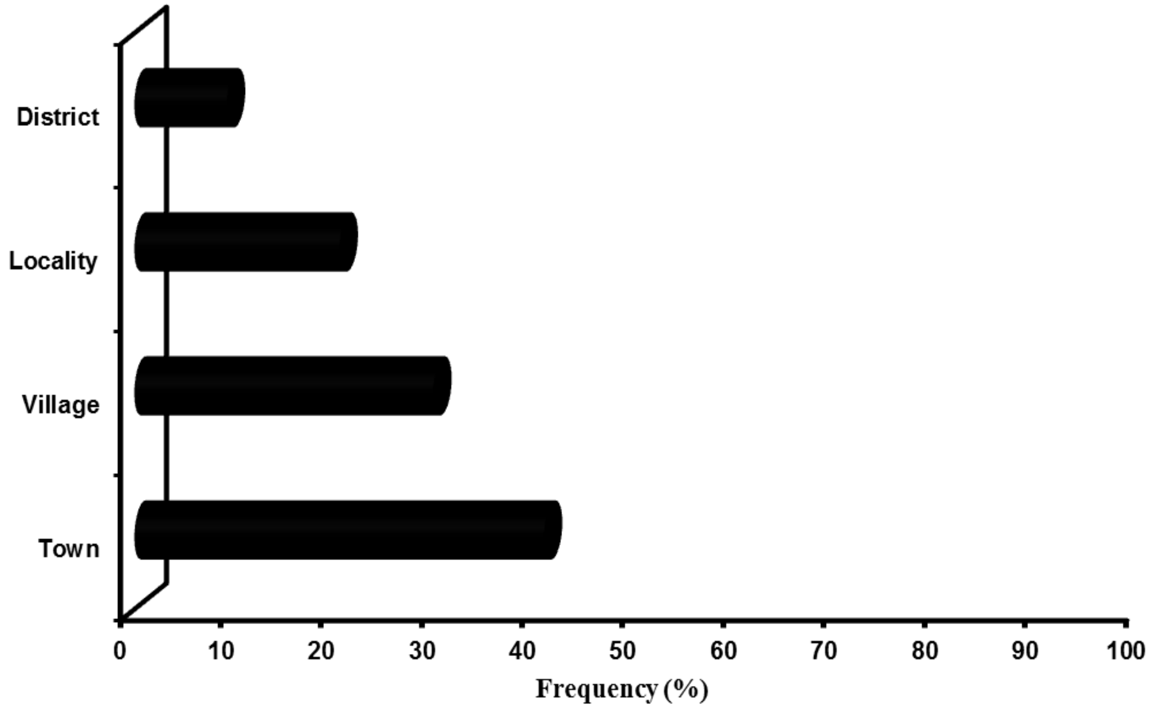

Figure 27: **Available Places for the Local Community to Sell their Products, with their Frequencies Based on the Responses of the Interviewed Participants, According to the Current Study Survey Conducted at Dinder Biosphere Reserve in the Year 2021, N = 270**

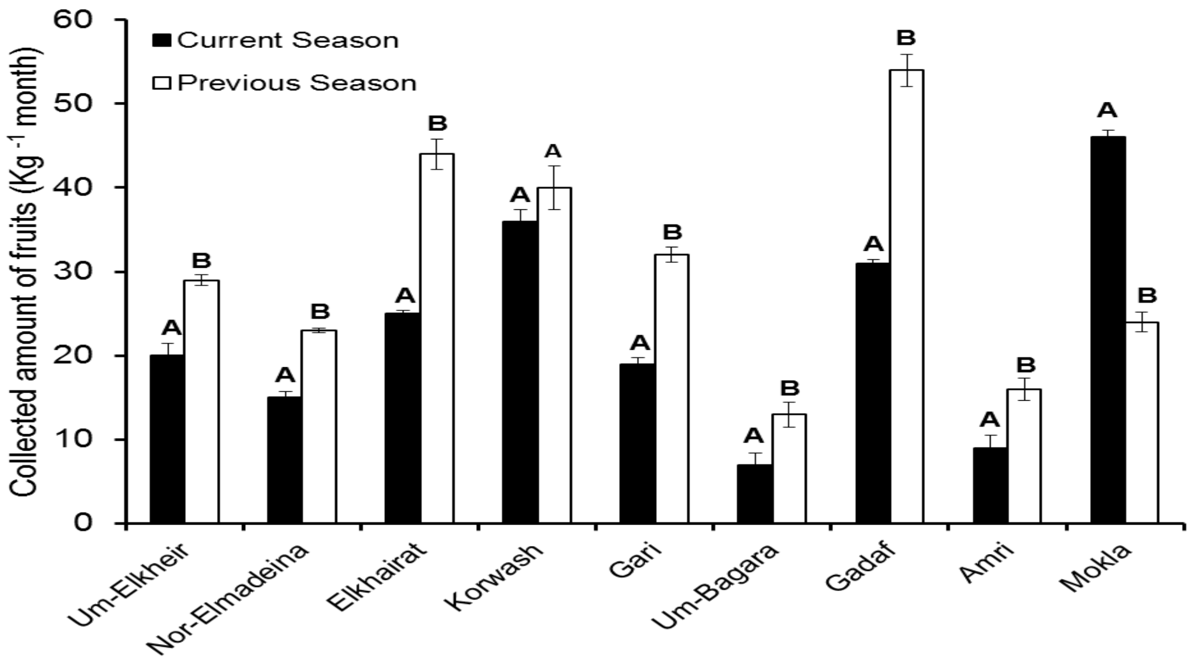

Figure 28: **Average (±SE) Collected Amount of *B. aegyptiaca* Fruits (Kg/month) During the Current and Previous Collecting Seasons for the Respondents from the Nine Selected Villages, According to the Current Study Survey Conducted at DBR in the Year 2021, N = 270**

(iv) The Rare and Disappeared Tree Species and their Limiting Factors

The survey findings showed that a total of twenty tree species had been listed by the participants as rare species (Table 11), and nine as disappeared (Table 12). A rare tree species is a species that is infrequently encountered in the field and not observed for three to five years, while disappeared ones are species that have not been seen for more than five years (FAO, 2015; Hassan & Tag, 2017). Although 60% of the rare tree species are still commonly used for food, feed, and medicine (Table 11), 66% of the disappeared ones were used as a fodder (Table 12). Moreover, most of the interviewed participants mentioned that overgrazing and illegal felling are the main reasons behind the decline of *B. aegyptiaca* tree species in the study area (35% and 31%, respectively, Fig. 29).

Table 11: Rare Tree Species within and Around the Dinder Biosphere Reserve as listed by 270 Respondents Interviewed Over Two Months, January to February 2021

No	Species	Uses
1	*Acacia drepanolobium*	Food, Fire wood & Medicine
2	*Acacia sieberiana*	Fodder & Fire wood
3	*Adansonia digitata*	Food, Fodder & Medicine
4	*Boscia senegalensis*	Fodder & fire wood
5	*Combretum molle*	Fodder, Building & Fire wood
6	*Commiphora africana*	Medicine & Fodder
7	*Cordia rothii*	Food, Fodder & Furniture
8	*Dalbergia melanoxylon*	Furniture & Building
9	*Gardenia lutea*	Fodder & Fire wood
10	*Grewia mollis*	Food & Fodder
11	*Grewia tenax*	Food & Fodder
12	*Lannea fruticosa*	Fodder & Fire wood
13	*Maerua crassifolia*	Medicine & Fodder
14	*Piliostigma reticulatum*	Fodder, Medicine, Furniture & fire wood
15	*Sterculia setigera*	Medicine
16	*Stereospermum kunthianum*	Fodder, Building & fire wood
17	*Terminalia brownii*	Building & Fire wood
18	*Terminalia laxiflora*	Building & Fire wood
19	*Terminalia macroptera*	Fire wood, Furniture & Building
20	*Ziziphus abyssinica*	Fodder & fire wood

Table 12: Disappeared Tree Species within and Around the Dinder Biosphere Reserve as Listed by 270 Respondents Interviewed Over Two Months, January to February 2021

No	Species	Uses
1	*Annona senegalensis*	Food, Fodder & Fire wood
2	*Capparis decidua*	Fodder & fire wood
3	*Diospyros mespiliformis*	Food, Fodder, Furniture & Fire wood
4	*Entada africana*	Fodder, Building & fire wood
5	*Lannea nigritana*	Fodder, Building & Fire wood
6	*Lannea schimperi*	Fodder, Building & Fire wood
7	*Sterculia africana*	Medicine
8	*Xeromphis nilotica*	Medicine & fire wood
9	*Ximenia americana*	Medicine & fire wood

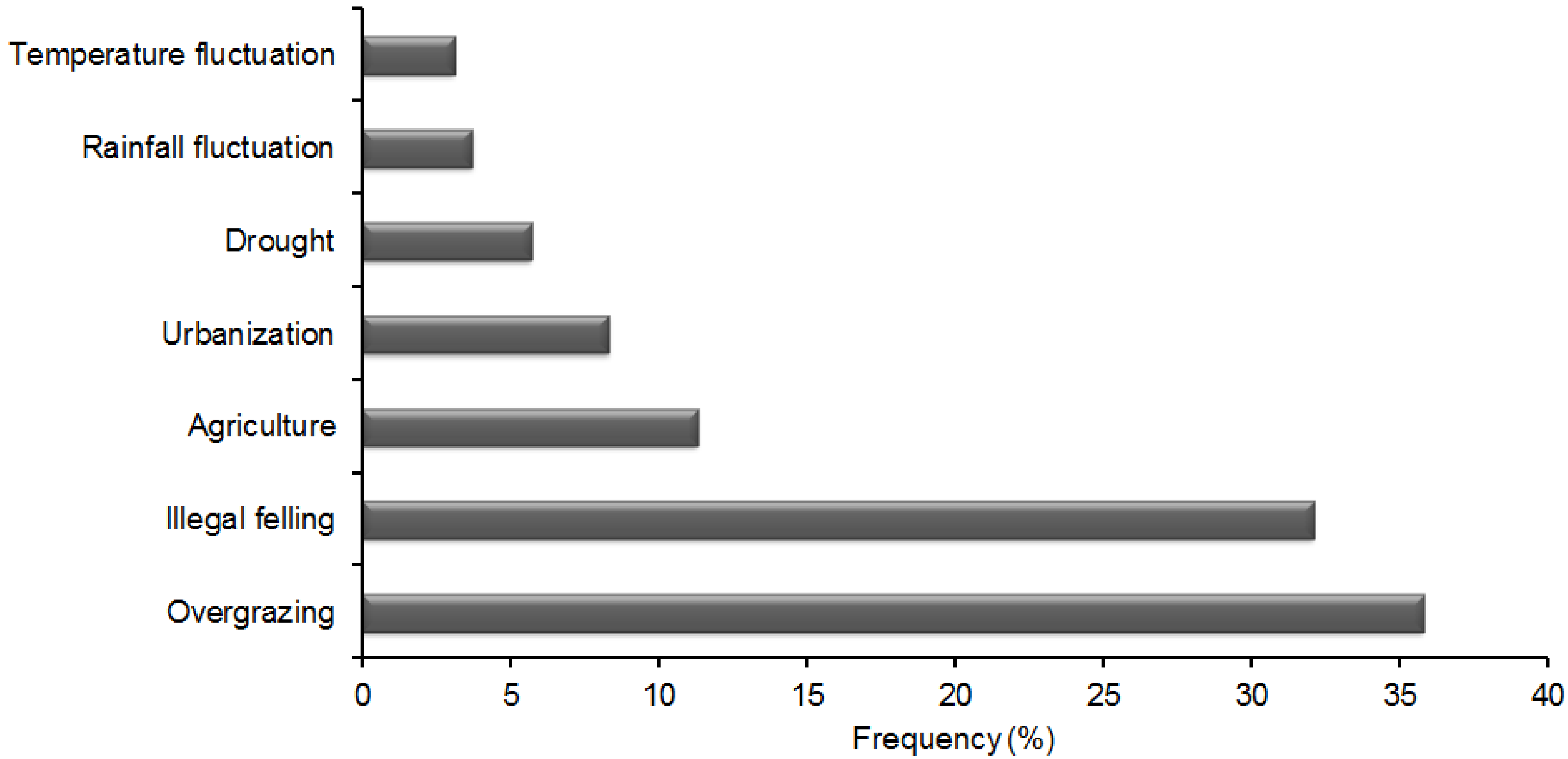

Figure 29: The Seven Most Commonly Mentioned Factors Contributing to the Decline of *B. aegyptiaca* within and Around the Dinder Biosphere Reserve According to Interviewees in Our Survey (2020 – 2021) at Dinder Biosphere Resereve; N = 270

4.2 Discussion

4.2.1 Exploring the Effects of Livestock Browsing and Illegal Felling on the Tree Species Diversity, Composition, and Growth of *B. aegyptiaca* in Dinder Biosphere Reserve

(i) High Diversity and Tree Density in Non-disturbed Site

The study demonstrated that the non-disturbed site has high species richness, tree diversity, and stand evenness compared to the disturbed site, which is in agreement with other scholars (Assogbadjo *et al*., 2010; Idrissa *et al*., 2018), who concluded similar results in Beinin and Niger, respectively. Moreover, limited number of tree species was abundant and dominant in the disturbed site. As diversified and heterogeneous tree communities are more healthy and tolerant to various biotic and abiotic disturbances (Bohn & Huth, 2017; Hofhansl *et al*., 2020; Kutnar *et al*., 2019; Lacerda & Kellermann, 2019; Simons *et al*., 2021), this finding already highlights the severity of anthropogenic activities in the disturbed site. A study conducted by Fakhry *et al*. (2020) reported that 75% of the woody plants in Jeddah, in Saudi Arabia, disappeared because of human pressure and climate variability, while Kutnar *et al*. (2019) and Tsegu (2019) mentioned that the tree diversity of Slovenian forests and agroforestry parklands in Ethiopia declined to a critical level due to deer browsing and livestock grazing, respectively. In contrast, other studies discussed the positive effects of low-intensity livestock grazing in enhancing the rangelands diversity and promoting forest heterogeneity and population dynamics (Hawkins, 2017; Lopez-Sanchez *et al*., 2014; Solar *et al*., 2016). Therefore, the low tree species richness in the disturbed sites of the Dinder Biosphere reserve is due to overgrazing, intensive browsing, and severe illegal harvesting in the sites that interrupted the normal tree growth and development. Therefore, to accelerate the natural recovery of trees in the reserve and auto-restoration of the disturbed sites, controlling the grazing by livestock and illegal harvesting is essential.

Anogeissus leiocarpus demonstrated an inverse trend with a considerable juvenile population in the disturbed sites compared to the non-disturbed sites. This is mainly because of the high illegal felling of mature trees in the disturbed sites for timber and medicinal uses. Researchers reported that *A. leiocarpus* was characterized by its highly durable wood at maturity and tannin contents at an earlier stage of development (Assogbadjo *et al*., 2010; Ball & Tzanopoulos, 2020; Ibrahim & Osman, 2014; Nyong *et al*., 2019; Salih *et al*., 2017). Therefore, the low palatability of its seedlings and saplings to livestock in the disturbed sites may have resulted from their tannin contents.

(ii) Low Dominance and Importance Value Index (IVI) in Non-disturbed Site

The current study found that fast-growing tree species such as *Acacia oerfota*, *Acacia polyacantha*, *Acacia senegal*, *Acacia seyal var fistula*, *Acacia sieberiana*, and *Acacia tortilis* were common in the disturbed site. However, as these tree species are rangeland-encroaching species (Ahmed & Desougi, 2014; Deng *et al*., 2016; Endale *et al*., 2017; Neelo *et al*., 2015), the degraded areas in the disturbed sites might be under bush encroachment. The current anthropogenic activities in the disturbed sites, together with this high population of *Acacia* species, led to the reduction of the *B. aegyptiaca* trees and disturbs its population dynamic. Researchers concluded the same result for *Anogeissus leiocarpus*, nut tree species, and medicinal tree species in Benin, Kyrgyzstan, Niger, and Sudan, respectively (Assogbadjo *et al*., 2010; Cantarello *et al*., 2014; Idrissa *et al*., 2018; Osman & Idris, 2012). Moreover, studies carried out by Gebru *et al*. (2019), Joel (2018), and Okia (2013) highlighted the sensitivity of *B. aegyptiaca* seedlings and saplings to the intensive bush encroachment and space competition. Others illustrated that the frequent browsing, overgrazing, *Acacia drepanolobium* encroachments, and the unmanaged exploitation of the forest and rangeland trees led to the elimination of valuable tree species in the natural forests and rangelands in Ethiopia, Tanzania, Botswana, and Uganda (Kochare *et al*., 2018; Ligate *et al*., 2019; Neelo *et al*., 2015; Weldemariam *et al*., 2017).

Furthermore, the highest IVI in the disturbed sites was for *Acacia seyal var seyal*, with significant differences to the closed species as an unambiguous sign of the unstable ecosystem and unbalanced habitat. The ecosystem instability may result from natural or anthropogenic disturbance which usually affects individual species as well as the entire community (Acácio & Holmgren, 2014; Gebeyehu *et al*., 2019; Ghanbari *et al*., 2021; Mwakosya & Mligo, 2014; Wang *et al.*, 2019). For the disturbed sites in DBR, both types were observed where the aggregated distribution patterns of *B. aegyptiaca* illustrated that seedlings and saplings were located in patches probably due to repeated human disturbances, while across species trend was shown by its low species richness compared to non-disturbed sites. Moreover, this finding proved that *B. aegyptiaca* was overutilized in this area, and urgent conservation measures are needed. This conclusion is consistent with findings of other researchers in similar habitats (Chapagain *et al*., 2009; Elfeel & Warrag, 2011; Hassan & Tag, 2017; Idrissa *et al*., 2018).

(iii) Better Growth, Distribution, and Dendrometric Parameters in Non-disturbed Site

This study findings showed that 86% of the current tree and shrub species in the disturbed sites have a limited young generation and very low regeneration state. Species like *Sterculia setigera*, *Commiphora africana, Stereospermum kunthianum,* and *Tamarindus indica* are only present at the adult stage. In contrast, 75% of the forest tree and shrub population in the non-disturbed sites were represented by the juveniles (seedlings and saplings), particularly *A. seyal var seyal, A. leiocarpus, B. aegyptiaca,* and *C. hartmannianum*. However, as all these species are native and growing naturally in the DBR and other rangelands and forests throughout the country (Elmoghraby & Abdu, 1985; Hassaballah *et al*., 2016; Ibrahim *et al*., 2018; Mohammed *et al*., 2021), climatic variability is equally affecting them; hence, the current decline is mainly attributed to biotic factors. Activities like the intensive collection of *B. aegyptiaca* fruits and harvesting of its crown branches for livestock feeding can minimize the species natural regeneration and hinder the recruitment of its seedlings and saplings. These results are consistent with the conclusions of other researchers (Aleza *et al*., 2018; Dunne *et al*., 2011; Gebrehiwot & Hundera, 2014; Ibrahim & Hassan, 2015; Kacholi, 2014; Mwakosya & Mligo, 2014; Nndwammbi *et al*., 2018), where severe extraction of non-timber forest products (NTFPs) and overgrazing reduced the tree stocking density, saplings growth, seedlings recruitment, and seedlings distribution in the open woodlands in Benin, Kenya, Ethiopia, Sudan, Tanzania, and South Africa, respectively.

The current study also found that the basal area contribution of *B. aegyptiaca* was low in the non-disturbed sites compared to disturbed ones, while other dendrometric parameters show better performance. Basal area contribution is proportionally correlated with the stand density, average tree height, and mean DBH (Bohn & Huth, 2017; Ibrahim *et al*., 2014; Storch *et al*., 2018; Vayreda *et al*., 2013). The lower basal area contribution in the non-disturbed sites of DBR could be attributed to the stocking density in these sites and their species heterogeneity. However, the low crown width in the disturbed sites is directly related to the tree debranching activities that are usually conducted by the locals. Tree species like *Quercus ithaburensis, Prosopis africana,* and *Quercus agrifolia* demonstrated a similar trend in Israel (Dufour-Dror, 2007), Niger (Abdou *et al*., 2016), and North California (Lopez-Sanchez *et al*., 2014), respectively. Therefore, the study highlighted that a monitoring program for the low-density areas should be introduced as a conservation approach to sustain this vulnerable tree species.

4.2.2 Identifying the Sensitive Stage at which *B. aegyptiaca* is most Affected by Livestock Browsing in Dinder Biosphere Reserve

(i) Seedling Survival, Mortality, Diameter, and Height

This study found that *B. aegyptiaca* seedlings had severely been affected by goat browsing in DBR. Similar results have been reported by other studies as well (Ball & Tzanopoulos, 2020; Li *et al*., 2013; Sanon *et al*., 2007; Tsegu, 2019). Ball and Tzanopoulos (2020), and Li *et al*. (2013) mentioned that goat browsing had extremely affected the growth of *Anogeissus dhofarica* and *Caragana intermedia* in Oman and Mongolia, respectively. While Sanon *et al.* (2007), and Tsegu, (2019) reported that seedlings of *Acacia senegal* and *Faidherbia albida* in Burkina Faso and Ethiopia, respectively, were dramatically disturbed by livestock browsing, and their population reduced to less than 50% of the total tree population.

Further, this study results illustrated that seedlings browsed by goats have stem diameter smaller in size by > 40% to the unbrowsed seedlings in the GOA, CAM, and CON. This highlights the severity of goat browsing compared to cattle and camel and the necessity of controlling such browsing to sustain vulnerable species like *B. aegyptiaca*. These results are in line with that of Maua *et al*. (2020), who reported that overgrazing and livestock browsing have suspended the growth of 25 native and useful tree species in Kenya and limited their natural regeneration.

While the height-density relationship of the *B. aegyptiaca* seedlings exhibited the same pattern throughout the study area, their slopes vary from one regression to another. This variation can be attributed to the differences in the grazing and browsing forms conducted by the various livestock species in the area where some are grazers, others are browsers, and others are multi-regimes. A study carried out in Greece by Lempesi *et al*. (2017) on the woody plants by using different browsing intensities (light, moderate, and severe) showed that the unbrowsed seedlings of *Quercus frainetto* gain more height, diameter, and density under light and moderate browsing compared to the limited one under severe browsing. Similar trends were observed in Ghana, Malawi, and Uganda for *Lannea schimperi*, *Blighia sapida*, and *Pinus kesiya*, respectively (Hammond *et al*., 2021; Missanjo *et al*., 2015; Ssegawa & Kasenene, 2007). Therefore, light browsing can be recommended as a good control measure for overstocked sites and not understocked ones.

(ii) Sapling Survival, Mortality, Diameter, and Height

The study results revealed that *B. aegyptiaca* saplings in the DBR have frequently been subjected to livestock browsing that reduced their survivals and interrupted their population dynamics. Such browsing over time can result in a tree population with only adult generation without seedlings and saplings (Carmona *et al*., 2013; Chaturvedi *et al*., 2012; Lopez-Sanchez *et al*., 2014; Mohammed *et al*., 2021), which will end up in the species extinction. Findings from

Mount Kilimanjaro and Parkland in Tanzania (Kikoti *et al*., 2015) and Niger (Bello & Jimoh, 2018; Idrissa *et al*., 2018) displayed similar conclusions.

A study performed by Dufour-Dror (2007) on the *Quercus ithaburensis* tree species in Tabor concluded that 50% of their saplings had been lost as a result of unmanaged livestock browsing and trampling. Moreover, Marone *et al*. (2017), Neya *et al*., (2019), Sagna *et al*. (2014), and Weber and Montes (2010) raised the same concerns in the Sahelian region of Africa for various native tree species that been grazed and browsed for a long period of time. Additionally, Hernández and Silva-Pando (1996) stated that Oak tree species in Spain deteriorated from 17 to 8 species under the combined deer and livestock browsing in the Galician Oak forest in the North-western part of the country. Such condition is very hazardous to *B. aegyptiaca*, particularly its saplings. Thus, the saplings of *B. aegyptiaca* in the DBR must be given more attention, especially those in the transition zone, where there are high anthropogenic activities and low natural regeneration.

(iii) Saplings Recovered Less than Seedlings under Cattle and Camel Browsing

The current study found that the number of healthy seedlings and the recovered ones after been browsed in CAT and CAM were higher than that of GOA. This can be justified based on the feeding habit of various livestock species found in the area. Goats usually browse young saplings and seedlings under 2 m in height (Kochare *et al*., 2018; Sanon *et al*., 2007), while camels, in contrast, browse the adult tree crowns (Ball & Tzanopoulos, 2020; Mohammed *et al*., 2021). However, cattle are by nature grazers which prefer herbaceous plants that constitute 95% of their daily forage (Dunne *et al*., 2011; Esquivel *et al*., 2008; Larson *et al*., 2015). Thus, the seedlings of *B. aegyptiaca* can be more palatable the cattle than saplings as the first ones are less hard and softer (Hanief *et al*., 2016; Larson *et al*., 2015; Maua *et al*., 2020; Osem *et al*., 2017; Tripathi *et al*., 2010).

The limited number of *B. aegyptiaca* saplings can directly be correlated to the extreme and repeated browsing, particularly goats which can browse, graze, and debark the main stem (Kochare *et al*., 2018; Lempesi *et al*., 2017; Luginbuhl *et al*., 2010; Poudel *et al*., 2019). Research conducted by Zamora *et al*. (2001) reported that 86% of *Pinus sylvestris* saplings in the natural forests at the Mediterranean mountains had been browsed several times by goats within the same season, and their growing shoots are continuously browsed, particularly during the dry season where herbaceous plants are scare. Besides that, Sher e*t al*. (2010) and Uddin *et al*. (2011) have mentioned that nomadic grazing in Pakistan and India had suspended the species diversity to less than 10%, and many medicinal and fodder tree species had disappeared. The lower recovery of *B. aegyptiaca* saplings in the DBR shows their sensitivity to livestock browsing, especially intensive ones.

Furthermore, this study reported limited mortalities in CON where there is no livestock. This site hosts various wild animals including, both grazers and browsers (Ahmed, 2005; Elmekki, 2008; Mahgoub, 2014; Mohammed *et al*., 2021). Species like African buffalo (*Syncerus caffer*), reedbuck (*Redunca redunca*), and bushbuck (*Tragelaphus sylvaticus*) can significantly contribute to this mortality of *B. aegyptiaca* seedlings and saplings. Studies have documented that buffalo usually damages juvenile seedlings and saplings through trampling and rarely browses them (Aremu & Onadeko, 2008; Megaze *et al.*, 2012). On the other hand, reedbuck can browse woody plants, which form more than 10% of their daily diet (Ahmed, 2005; Derebe & Girma, 2020). However, literature highlighted that their feeding regimes depend on the season (Ahmed, 2005; Derebe & Girma, 2020; Gill, 2000), food accessibility (Mahgoub, 2014; Treydte *et al*., 2006; Wassie, 2011), and the density of these wild animals themselves (Elmoghraby & Abdu, 1985; Fahmi, 2017; HCENR, 2004; Pfeifer *et al*., 2012). Therefore, the presence of buffalo and reedbuck can slightly influence the seedlings and saplings of *B. aegyptiaca* as their browsing activities are limited. Accordingly, as bushbucks prefer browsing woody plant than grazing herbaceous ones (Bayih & Yihune, 2018), the study claim that seedlings and saplings mortalities in the control site is commonly due to bushbuck browsing and not buffalo or reedbuck.

4.2.3 Assessing the Effect of Illegal cutting of *B. aegyptiaca* Branches on Tree Survival, Fruit Production, and Seedling Recruitment in Dinder Biosphere Reserve

(i) Largest Crown Width, Height, and most Fruiting Branches in Non-disturbed Site

The study findings of smaller tree crown width and height in the disturbed site agree with those studies which concluded that anthropogenic disturbances, particularly illegal harvesting, affected the population structure and reduced tree dendrometric parameters such as diameter, height, and crown width, in Niger, Benin, Sudan, and Botswana, respectively (Abdou *et al*., 2016; Assogbadjo *et al*., 2010; Mohammed *et al*., 2021; Neelo *et al*., 2015). Moreover, Fakhry *et al*. (2020), Idrissa *et al*. (2018), and Maua *et al*. (2020) found that intensive pruning, illegal logging, and overexploitation damaged the growth and development of *Cyperus conglomeratus, B. aegyptiaca*, and *Kigelia africana* in Saudi Arabia, Niger, and Kenya, respectively. This study also observed frequent illegal harvesting of twigs, leaves, bark and young branches for livestock feeding and medicinal uses in addition to cutting of trees for timber and firewood in the area.

Further, the strong positive correlation between the crown width and the number of fruiting branches document that fruit production is directly related to the tree dendrometric parameters, and any form of damage to tree diameter, crown, or height will affect this production process. Various studies on different fruiting forest trees showed similar results (Abdou *et al*., 2015; Bondé *et al*., 2019; Djekota *et al*., 2014; Haarmeyer *et al*., 2013; Lompo *et al*., 2018; Shackleton, 2002). Severe stem debarking and foliage harvesting eliminated the fruit production of *Afzelia africana* trees in Burkina Faso to > 95% (Nacoulma *et al*., 2016), while climate, land use, and unmanaged logging activities were the main factors that reduced the fruits of *Ximenia americana*, *B. aegyptiaca*, and *Swietenia macrophylla* trees to critical levels in the tropical forests in Burkina Faso and Mexico, respectively (Lompo *et al*., 2018; Ouédraogo *et al*., 2019; Snook *et al*., 2005). The limited fruit production of *B. aegyptiaca* in the disturbed site of the Dinder Biosphere Reserve can be attributed to the overutilization and rigorous pollarding activities by the local community in and around the reserve. Therefore, the study recommend that awareness-raising programs are urgently needed as well as an integrated management system that will consider the participation of local communities in the administration.

(ii) Lowest Seedling, Sapling, and Tree Density in the Disturbed Site

Results illuminate that the density of adult trees in the undisturbed sites was three times that in the disturbed sites, and the number was negatively correlated with the average number of fruiting branches. These findings are consistent with studies which reported that overgrazing, intensive browsing, and selective harvesting reduced more than 47% of mature trees and 40% of juvenile trees in mountainous forests of Oman, tropical dry forests of India, and the natural forests of Sudan, respectively (Ball and Tzanopoulos 2020; Chaturvedi *et al*., 2012; Ibrahim and Hassan 2015; Osman and Idris 2012). Other researchers stated that the frequent abiotic and biotic disturbances including anthropogenic pressure reduced the tree species density and excluded some valuable tree species from the natural forests and rangelands in Sudan, Tanzania, Slovenia, and Saudi Arabia (Fakhry *et al*., 2020; Kikoti & Mligo, 2015; Kutnar *et al*., 2019; Mohammed *et al*., 2021). Besides that, Ranaivoson *et al*. (2015) documented that up to 90% of *Tamarindus indica* tree loss in the south-western Madagascar forests was due to the charcoal production as well as slash and burn agriculture.

As hypothesized, the study results revealed that the density of seedlings and saplings in the disturbed sites represented only 50% of the ones in the undisturbed sites and were positively related to the average number of fruiting branches. The study conducted by Ouédraogo *et al*.

(2019) in the tropical areas of Burkina Faso concluded that there is a strong positive relationship between fruit production, crown cover, and the recruitments of *B. aegyptiaca* seedlings and saplings. Tree species diversity, seedling and sapling density, recruitment and stand composition were strongly associated with mature tree basal area and the severity of human intervention, as well as abiotic factors in the area (Gebeyehu *et al*., 2019; Ghanbari *et al*., 2021; Hammond *et al*., 2021; Hasoba *et al*., 2020; Uddin *et al*., 2011). However, the currently observed lower density of *B. aegyptiaca* seedlings and saplings in the disturbed sites of Dinder Biosphere Reserve could be attributed to the over-collection of the species fruits by the local community for food, feed, and medicinal uses. During the fieldwork activities this study documented the presence of considerable herds of livestock, particularly goats and cattle, in the western and southern parts of the reserve, which might be the main reason behind the degradation of new regeneration in that area, which was also supported by Mohammed *et al*. (2021) who quantified goat browsing effects on seedlings and saplings of *B. aegyptiaca*.

4.2.4 Quantifying the Differences in the Soil Chemical Properties Beneath the Affected and Healthy Trees in Dinder Biosphere Reserve

Soil nitrogen, organic carbon, potassium, and phosphorus were all higher beneath trees growing in our undisturbed sites compared with the disturbed sites. However, generally, within the site, the contents of nitrogen and phosphorus under other tree species were higher than those under *B. aegyptiaca* tree species. A high N content under other tree species may result from the contribution of nitrogen-fixing species (*Acacia seyal*, *Acacia senegal*, *Acacia polyacantha*, and *Acacia mellifera*) which were the second-most dominant species at the undisturbed sites. *Acacia senegal* and *A. seyal* can strongly enhance soil N and nutrient cycling (Abaker *et al*., 2018; Deng *et al*., 2016; Githae *et al*., 2011; Isaac *et al*., 2011; Omar & Muhammad 2016; Raddad *et al*., 2006). The current study findings show that the contribution of mature trees to soil fertility, through leaf litter and nutrient cycling, might be of high importance for DBR. This is consistent with Treydte *et al*. (2009) who reported that trees with large crown-size added 40% more N and P to the soil than smaller trees in South African savannas. Globally, logging activities, logging traffic, and illegal harvesting accelerated the soil degradation and reduced the soil nitrogen, organic carbon, and phosphorus in the tropical rain forests in Nigeria, natural forests in Washington and Oregon in the USA, humid tropical forests in Rondonia in Brazil, and the tropical savannah forests in Malawi, respectively (Adekunle & Olagoke, 2011; Jurgensen *et al*., 1997; Martinelli *et al*., 2000; Missanjo & Kamanga-thole, 2014).

Many studies have mentioned the importance of *B. aegyptiaca* as an agroforestry tree species characterized by its ability to improve the eroded soils and increase its productivity (Chapagain *et al*., 2009; Elfeel *et al*., 2007; Idrissa *et al*., 2018; Mohammed *et al*., 2021; Okia 2013). Moreover, as the species have widely been used in Sudan for food, feed, and medicinal purposes (Adam *et al*., 2013; Fadl 2015; Mohammed *et al*., 2021), the current study claim that the current declines in the soil chemical properties in the disturbed sites can directly be related to the overexploitation of the species and its products in the area. Therefore, intensive patrolling and monitoring is needed particularly in the western parts of the biosphere. In addition, the introduction of community forestry in the expanded area of the transition zone can reduce the current anthropogenic pressure and facilitate the restoration of the degraded areas.

4.2.5 Evaluating the Influence of the Possible *B. aegyptiaca* Population Decline on the income of Local People within and around Dinder Biosphere Reserve

(i) Socio-Demographic Characteristics of the Study Participants

The demographic and social characteristics of the surveyed participants show that women are more involved in non-timber forest products (NTFPs) business than men, while the majority of engaged people are young at age range between 21 to 30 years old. This illustrates that females are more familiars with the importance of NTFPs as well as their various uses, general status, and distribution in the reserve. Therefore, for any monitoring, conservation or management program, women must be at its core. Researchers stated that women are the main pillar of NTFPs in Sudan as they represented 75%, 80%, 77%, and 92% of this business in the Blue Nile, Kordofan, and Darfur, respectively (Abdelrahim, 2015; Adam *et al*., 2013; Khamis & Abdalla, 2017; Younis *et al*., 2018).

The study also found, most of the locals in and around the Biosphere are NTFPs collectors and agro-pastoralists with primary (35%) and secondary education (30%), this elucidates why the transition zone of the DBR is under high anthropogenic pressure due to the NTFPs collection processes and livestock rearing. Although agro-pastoralist usually combines farming and livestock rearing as their income generation activities (Ali *et al*., 2009; Endale *et al*., 2017; Weber & Montes, 2010), pastoralists are just keeping livestock with limited NTFPs trade (Gamoun *et al*., 2015; Ligate *et al*., 2019; Riginos *et al*., 2009). Thus, consideration of the local community gender, age groups, education, and occupations are the key points to set a proper sustainable management plan for *B. aegyptiaca* in the disturbed sites of the DBR.

(ii) The Ten Top most Utilized Tree Species for Food, Medicine, Fodder, and Building

The study findings have illuminated how *B. aegyptiaca* has intensively been utilized for food, feed, and medicine. More than 30% of the study respondents declared that they used this multipurpose tree species as a medicine to cure various diseases, including malaria, stomach illness, diarrhea, skin diseases, and yellow fever. Literature proved the significance of *B. aegyptiaca* as a medicinal plant, where other researchers proved the potential of the species extracts as antibacterial, antimicrobial, and anticancer drugs, respectively (Manandhar *et al*., 2019; Tula *et al*., 2014; Khamis *et al*., 2020; Murthy *et al*., 2021; Singh *et al*., 2017; Hassanin *et al*., 2018; Khatoon *et al*., 2013; Murthy *et al*., 2021). Other studies revealed the importance of *B. aegyptiaca* as a fodder tree, especially in the Sahel during the dry seasons (Abdelaziz *et al*., 2020; Marone *et al*., 2017; Mohammed *et al*., 2021; Ouédraogo *et al*., 2019; Sagna *et al*., 2014). The current high utilization of the species in the study area necessitates the urgent need for introducing a sustainable management policy that will fulfill the needs of the local community as well as conserve the species. This is very important as the present management plan gives more consideration to wild animals than trees.

This study also found that *Anogeissus leiocarpus, Ziziphus spina-christi,* and *Combretum hartmannianum* were the top preferable tree species by the participants for building purposes. Similarly, other studies mentioned the durability of *Anogeissus leiocarpus* wood that made it among the top building materials for the most forest-based communities in Africa, particularly in the sub-Saharan countries (Assogbadjo *et al*., 2010; Ball & Tzanopoulos, 2020; Barku *et al*., 2013; Bello & Jimoh, 2018; Mukhtar *et al*., 2017). Moreover, other studies as well documented that *Ziziphus spina-christi* and *Combretum hartmannianum* have been used as a building material because the first ones have a flexible timber and can easily be shaped while it is green, while the second ones have straight wood which is commonly used for roofing purposes (Adam *et al.*, 2013; Beche *et al*., 2016; Gebru *et al*., 2019; Ibrahim & Osman, 2014; Neelo *et al*., 2015; Niass *et al*., 2016). However, selective cutting of these species can negatively influence their population and hinder their sustainability. Therefore, the management of DBR needs to conduct an awareness-raising program to reduce the impacts of such activities, including the intensive collection of *B. aegyptiaca* fruits, and protect these species.

(iii) Better Revenue and Markets in Town

The study found that 40% of the collected *B. aegyptiaca* fruits and their products were sold at the town markets. This fact highlights that utilization of this species is not only limited to the reserve rather reaches various NTFPs markets across the country. The findings of this study are consistent with other studies which stated that NTFPs trade is widely spread in the Sudan. Although the collected amounts significantly vary from one area to another and from season to season, their contribution as a poverty alleviation means is relative (Adam *et al*., 2013; Fadl, 2015; Hasoba *et al*., 2020; Idrissa *et al*., 2018; Younis *et al*., 2018). Different forest-based communities satisfy their daily demands from forests and forest products, as well as income raising (Ahenkan & Boon, 2011; Maruod *et al*., 2014; Suleiman *et al*., 2017). In contrast, other studies showed that small dealers and mediators are more at the village and locality levels than in town (Joel, 2018; Manji *et al*., 2013; Okia, 2013). As Dinder is surrounded by three states (Gedaref, Sinnar, and Blue Nile) and more than 24 villages with different ethnic groups, interests, and cultures, marketing of their NTFPs is very easy; however, concerns on the regulated yield must be expressed, to ensure the continuity of these resources from generation to another. Besides that, the study recommended that value chain analysis for *Adansonia digitata, Balanites aegyptiaca*, *Grewia mollis*, *Grewia tenax*, *Tamarindus indica*, and *Ziziphus spina-christi* must be conducted as a prerequisite towards the formulation of future NTFPs policy for the reserve.

(iv) The Rare and Disappeared Tree Species and their Limiting Factors

The respondents of this study survey identified 20 tree species as rare species in the biosphere with limited distribution to the core zone. 60% of these species are used for medicine, food, and feed. There is a clear correlation between the species population decline, anthropogenic pressure, and the stage of development for these species. This finding is directly associated with objectives 2 and 3 results, and they are in line with other studies as well (Aubad *et al*., 2008; Ravenel, 2004; Reboredo, 2013; Reuter *et al*., 2018). Moreover, result suggests that, more than 30% of the interviewed respondents pointed-out that the main factors behind the degradation of the natural woodlands in DBR and dramatic decline of *B. aegyptiaca* population are livestock grazing and illegal harvesting. This result confirm the hypothesis that study on the severity of intensive livestock browsing, overgrazing, and illegal cutting in interrupting the species growth, development, and their ability to recruits the new generations. Similarly, other scholars exhibited the same trends for others woody, medicinal, and foraging forest tree species (Cantarello *et al*., 2014; Chaturvedi *et al*., 2012; Derebe & Girma, 2020; Ibrahim & Hassan, 2015; Mohammed *et al*., 2021; Osman & Idris, 2012).

The study found that 9 tree species have become extinct from the study area (*Annona senegalensis*, *Capparis decidua*, *Diospyros mespiliformis*, *Entada africana*, *Lannea nigritana, Lannea schimperi, Sterculia africana*, *Xeromphis nilotica*, and *Ximenia americana*), mainly due to the livestock feeding (66%). This considerable number of disappeared species raises an alert for the reserve management to set a conservation plan that will protect these vulnerable tree species and maintain their remaining populations. Researchers reported that combined activities of grazing and illegal felling can eliminate the mother fruit-producing trees, reduce the establishment of new juvenile stands, and minimize their species richness (Kikoti *et al*., 2015; Riba, 1998; Vayreda *et al*., 2013; Zeng *et al*., 2017). While the interviewed respondents highlighted the severity of browsing and illegal harvesting on the species composition, diversity, survival, and sustainability, other factors like agriculture expansion and urbanization, must also be considered if we want to tackle the dramatic increase of human population size in the area. Ecologists linked the deteriorations of forest biodiversity, species richness declines, and gene drift in the natural habitats, to the increases of human populations in and around the forest lands, and their high urbanization rate (Asigbaase *et al*., 2019; Chen & Tang, 2016; Ghanbari *et al*., 2021; Hawkins, 2017). Thus, to reduce current declines of the tree species in DBR and to ensure that disturbed sites will recover, a new working plan must be formulated based on these findings and their socio-demographic component.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The study found that disturbed sites in DBR encompass low tree diversity, richness, and young generations (seedlings and saplings) compared to that of non-disturbed sites. The natural regeneration of *B. aegyptiaca* in the disturbed sites of DBR has been extremely affected by the intensive livestock browsing, overgrazing, and illegal felling, and many spaced areas have been occupied by the bush-encroaching species such as *Acacia mellifera*, *Acacia polyacantha* and *Acacia seyal*. The study also confirmed that *Adansonia digitata*, *Lonchocarpus laxiflorus, Sterculia setigera*, and *Tamarindus indica* have the lowest importance value index, and among them, some are found only as adults without regeneration.

Current findings conclude that seedlings of *B. aegyptiaca* recover better than their saplings under cattle and camel browsing. However, goats proved to be the most destructive livestock browser in the area as they eliminated more than 60% of the species seedlings in the study site. The study claim that *B. aegyptiaca* saplings are not palatable to the cattle, and therefore, they can be permitted to graze in such area.

The study further conclude that tall trees with large crown widths produce the largest number of fruiting branches and contribute strongly to the soil nutrient contents, tree proliferation, and species resilience in the reserve. Additionally, the study concludes that the current degradation of soil fertility in DBR will consequently affect the fruit production and seedling recruitment processes in the reserve in the coming times.

This study also illustrated that women were more involved in the NTFPs business than men, with primary to secondary education and at an age group in range of 21 to 30 years old. However, twenty, nine tree species have been reported as rare and disappeared species, respectively. Moreover, *B. aegyptiaca* appears to be the first top species for food, feed, and medicinal purposes in the area with lower building applications.

5.2 Recommendations

Following recommendations must be considered towards the effective utilization of the study findings and their potentials:

(i) The study recommended that goat grazing and browsing must be controlled and reduced to allow the seedlings and saplings to grow and evolve to the next stage of tree development.

(ii) Stem debarking, uprooting, leaf defoliation, pollarding, and illegal logging should be prohibited and regulated through strict policies.

(iii) Awareness-raising programmes are urgently needed to minimize the observed over-exploitation of *B. aegyptiaca* fruits and increase the reserve soil seed bank.

(iv) Introduction of monitoring programmes in the disturbed sites of DBR are also required, particularly in the western and southern parts of the transition zone, where seedlings and saplings were dramatically declining.

(v) *B. aegyptiaca* tree populations decline was unambiguously influenced by the anthropogenic disturbances, this highlighten the needs for quick response to protect the tree species, particularly the rare ones like *Adansonia digitata, Sterculia setigera*, and *Tamarindus indica*.

(vi) Community forests can be established in the degraded farms outside the biosphere in order to reduce the pressure on the reserve resources.

(vii) More researches are demanded regarding the influences of wild animals browsing on the seedlings and saplings of *B. aegyptiaca* and how that can affect the species sustainability.

(viii) To reduce the effects of *B. aegyptiaca* removal in the agro-pastoral areas for agricultural purposes, the introduction of agroforestry and the intercropping system is highly recommended.

REFERENCES

Abaker, W. E., Berninger, F., Saiz, G., Pumpanen, J., & Starr, M. (2018). Linkages between soil carbon , soil fertility and nitrogen fixation in *Acacia senegal* plantations of varying age in Sudan. *Peer Journal*, *6*(e5232), 1–22. https://doi.org/10.7717/peerj.5232

Abdallah, E. M., Hsouna, A. B., & Al-khalifa, K. S. (2012). Antimicrobial, antioxidant and phytochemical investigation of *Balanites aegyptiaca* (L.) Del . edible fruit from Sudan. *African Journal of Biotechnology*, *11*(52), 11535–11542. https:// doi. org/ 10. 5897/ AJB12.1102

Abdel-Motaal, A., El-Askary, H., Crockett, S., Kunert, O., Sakr, B., Shaker, S., Grigore, A., Albulescu, R., & Bauer, R. (2015). Aldose reductase inhibition of a saponin-rich fraction and new furostanol saponin derivatives from *Balanites aegyptiaca*. *Phytomedicine*, *22*(9), 829–836. https://doi.org/10.1016/j.phymed.2015.05.059

Abdelaziz, S. M., Lemine, F. M. M., Tfeil, H. O., Filali-Maltouf, A., & Boukhary, A. O. M. S. (2020). Phytochemicals, antioxidant activity and ethnobotanical uses of *Balanites aegyptiaca* (L.) del. fruits from the arid zone of mauritania, Northwest Africa. *Plants*, *9*(3), 9–12. https://doi.org/10.3390/plants9030401

Abdelrahim, M. (2015). Contribution of Non-wood Forest Products in Support of Livelihoods of Rural People Living in the Area South of Blue Nile State, Sudan. *International Journal of Agriculture, Forestry and Fisheries*, *3*(5), 189–194.

Abdou, L., Guimbo, I. D., Chaibou, I., & Mahamane, A. (2015). Fruit production of *Prosopis africana* (G. et Perr.) Taub., an overexploited species in the Southeastern Niger. *International Journal of Current Microbiology and Applied Sciences*, *4*(5), 50–56. http://www.ijcmas.com

Abdou, L., Morou, B., Abasse, T., & Mahamane, A. (2016). Analysis of the structure and diversity of *Prosopis africana* (G. et Perr.) Taub. Tree stands in the Southeastern Niger. *Journal of Plant Studies*, *5*(1), 58-67. https://doi.org/10.5539/jps.v5n1p58

Abou-Khalil, N. S., Abou-Elhamd, A. S., Wasfy, S. I. A., El Mileegy, I. M. H., Hamed, M. Y., & Ageely, H. M. (2016). Antidiabetic and Antioxidant Impacts of Desert Date (*Balanites aegyptiaca*) and Parsley (*Petroselinum sativum*) Aqueous Extracts: Lessons from

Experimental Rats. *Journal of Diabetes Research*, *2016*(1), 1–10. https:// doi. org/ 10. 1155/ 2016/ 8408326

Acácio, V., & Holmgren, M. (2014). Pathways for resilience in Mediterranean cork oak land use systems. *Annals of Forest Science*, *71*(1), 5–13. https://doi.org/10.1007/s13595-012-0197-0

Adam, Y. O., Pretzsch, J., & Pettenella, D. (2013). Contribution of non-timber forest products livelihood strategies to rural development in drylands of Sudan: Potentials and failures. *Agricultural Systems*, *117*, 90–97. https://doi.org/10.1016/j.agsy.2012.12.008

Adekunle, V. A. J., & Olagoke, A. O. (2011). The impacts of timber harvesting on residual trees and seedlings in a tropical rain forest ecosystem , southwestern Nigeria. *International Journal of Biodiversity Science, Ecosystem Services & Management*, *6*(3–4), 131–138. https://doi.org/10.1080/21513732.2010.534976

Ahenkan, A., & Boon, E. (2011). Improving nutrition and health through non-timber forest products in Ghana. *Journal of Health, Population and Nutrition*, *29*(2), 141–148. https://doi.org/10.3329/jhpn.v29i2.7856

Ahmed. (2005). *The Biology of the Reedbuck* (*Redunca redunca* pallay, 1764) *in Dinder National Park*. University of Khartoum.www.google.

Ahmed, A. T., & Desougi, M. A. (2014). The Ecology of Some Gum Tree Species and Their Uses at Tozi Natural Forest, Sinnar State, Sudan. *Journal of Natural Resources & Evironmental Studies*, *6456*(6), 29–35.

Al-thobaiti, S. A., & Abu Zeid, I. M. (2018). Medicinal properties of desert date plants (*Balanites aegyptiaca*): An overview. *Global Journal of Pharmacology*, *12*(1), 1–12. https:// doi. org/ 10. 5829/idosi.gjp.2018.01.12

Alansari, A. K. A., & Al-thobaiti, S. A. (2021). *Balanites aegyptiaca* kernel extract (Desert Date) protects against Diabetes-induced Cardiomyopathy in Rats: A histological and biochemical Study. *Journal of the North for Basic and Applied Sciences*, *6*(1), 55–65. https:// doi. org/ 10. 12816/ 0058338

Aleza, K., Villamor, G. B., Nyarko, B. K., Wala, K., & Akpagana, K. (2018). Shea (*Vitellaria paradoxa* Gaertn C. F.) fruit yield assessment and management by farm households in the Atacora district of Benin. *PLoS ONE*, *13*(1), 1-20. https:// doi. org/ 10. 1371/ journal. pone.

0190234

Ali, I. A., Bongo, A., & El Tahir, B. A. (2009). *The role of scientific research in agricultural development.* www.google.com

Aremu, T. O., & Onadeko, A. S. (2008). Nutritional Ecology of African Buffalo (*Syncerus caffer nanus*). *International Journal of Agricultural Research*, *3*(4), 281–286.

Arosa, M. L., Bastos, R., Cabral, J. A., Freitas, H., Costa, S. R., & Santos, M. (2017). Long-term sustainability of cork oak agro-forests in the Iberian Peninsula: A model-based approach aimed at supporting the best management options for the montado conservation. *Ecological Modelling*, *343*, 68–79. https://doi.org/10.1016/j.ecolmodel.2016.10.008

Asigbaase, M., Sjogersten, S., Lomax, H. B., & Dawoe, E. (2019). Tree diversity and its ecological importance value in organic and conventional cocoa agroforests in Ghana. *PLoS ONE*, *14*(1), 1–19. https://doi.org/10.1371/journal.pone.0210557

Assogbadjo, A. E., Kakaï, R. L. G., Sinsin, B., & Pelz, D. (2010). Structure of *Anogeissus leiocarpa* Guill., Perr. natural stands in relation to anthropogenic pressure within Wari-Maro Forest Reserve in Benin. *African Journal of Ecology*, *48*(3), 644–653. https:// doi. org/ 10.1111/ j.1365-2028.2009.01160.x

Aubad, J., Aragón, P., Olalla-Tárraga, M. Á., & Rodríguez, M. Á. (2008). Illegal logging, landscape structure and the variation of tree species richness across North Andean forest remnants. *Forest Ecology and Management*, *255*(5–6), 1892–1899. https:// doi. org/ 10. 1016/ j. foreco.2007.12.011

Ball, L., & Tzanopoulos, J. (2020). Livestock browsing affects the species composition and structure of cloud forest in the Dhofar Mountains of Oman. *Applied Vegetation Science*, *23*(3), 363–376. https://doi.org/10.1111/avsc.12493

Barku, V. Y. A., Boye, A., & Ayaba, S. (2013). Phytochemical screening and assessment of wound healing activity of the leaves of *Anogeissus leiocarpus*. *European Journal of Experimental Biology*, *3*(4), 18–25. www.pelagiaresearchlibrary.com

Basheer, A. K., Lu, H., Omer, A., Ali, A. B., & Abdelgader, A. M. S. (2016). Impacts of climate change under CMIP5 RCP scenarios on the streamflow in the Dinder River and ecosystem habitats in Dinder National Park, Sudan. *Hydrology and Earth System Sciences*, *20*(4), 1331–1353. https://doi.org/10.5194/hess-20-1331-2016

Bayih, W., & Yihune, M. (2018). Population status, feeding ecology and activity pattern of common bushbuck (*Tragelaphus Scriptus decula*) in Sekele Mariam Forest, West Gojjam, Ethiopia. *Journal of Ecology and The Natural Environment*, *10*(5), 69–79. https:// doi. org/ 10. 5897/jene2018.0689

Beche, D., Gebeyehu, G., & Feyisa, K. (2016). Indigenous utilization and management of useful plants in and around Awash National Park, Ethiopia. *Journal of Plant Biology & Soil Health*, *3*(1), 1–12. https://doi.org/10.13188/2331-8996.1000008

Beiske, B. (2007). Research Methods. Uses and Limitations of Questionnaires, Interviews, and Case Studies. https://www.google.com

Bello, A. A., & Jimoh, A. A. (2018). Some physical and mechanical properties of African birch (*Anogeissus leiocarpus*) timber. *Journal of Applied Sciences and Environmental Management*, *22*(1), 1119-8362. https://doi.org/10.4314/jasem.v22i1.14

Beltrán-Rodríguez, L., Valdez-Hernández, J. I., Saynes-Vásquez, A., Blancas, J., Sierra-Huelsz, J. A., Cristians, S., Martínez-Ballesté, A., Romero-Manzanares, A., Luna-Cavazos, M., de la Rosa, M. A. B., Pineda-Herrera, E., Maldonado-Almanza, B., Ángeles-Pérez, G., Ticktin, T., & Bye, R. (2021). Sustaining medicinal barks: Survival and bark regeneration of *Amphipterygium adstringens* (anacardiaceae), a tropical tree under experimental debarking. *Sustainability (Switzerland)*, *13*(5), 1–19. https://doi.org/10.3390/su13052860

Bohn, F. J., & Huth, A. (2017). *The importance of forest structure to biodiversity-productivity relationships.* https://www.google.com

Bondé, L., Ouédraogo, O., Ouédraogo, I., Thiombiano, A., & Boussim, J. I. (2019). Variability and estimating in fruiting of shea tree (*Vitellaria paradoxa* C.F. Gaertn) associated to climatic conditions in West Africa: Implications for sustainable management and development. *Plant Production Science*, *22*(2), 143–158. https://doi.org/10.1080/1343943X.2018.1541712

Burman, S., Bhattacharya, K., Mukherjee, D., & Chandra, G. (2018). Antibacterial efficacy of leaf extracts of *Combretum album* Pers. against some pathogenic bacteria. *Complementary and Alternative Medicine*, *18*(1), 1–8. https://doi.org/10.1186/s12906-018-2271-0

Cantarello, E., Lovegrove, A., Orozumbekov, A., Birch, J., Brouwers, N., & Newton, A. C. (2014). Human impacts on forest biodiversity in protected Walnut-fruit forests in Kyrgyzstan. *Journal of Sustainable Forestry*, *33*(5), 454–481. https:// doi. org/ 10. 1080/ 10549811. 2014. 901918

Carmona, C. P., Azcárate, F. M., Oteros-Rozas, E., González, J. A., & Peco, B. (2013). Assessing the effects of seasonal grazing on holm oak regeneration: Implications for the conservation of Mediterranean dehesas. *Biological Conservation*, *159*, 240–247. https:// doi. org/ 10. 1016/ j.biocon.2012.11.015

Chapagain, B. P., Yehoshua, Y., & Wiesman, Z. (2009). Desert date (*Balanites aegyptiaca*) as an arid lands sustainable bioresource for biodiesel. *Bioresource Technology*, *100*(3), 1221–1226. https://doi.org/10.1016/j.biortech.2008.09.005

Chaturvedi, R. K., Raghubanshi, A. S., & Singh, J. S. (2012). Effect of grazing and harvesting on diversity, recruitment and carbon accumulation of juvenile trees in tropical dry forests. *Forest Ecology and Management*, *284*, 152–162. https://doi.org/10.1016/j.foreco.2012.07.053

Chen, J., & Tang, H. (2016). Effect of grazing exclusion on vegetation characteristics and soil organic carbon of *Leymus chinensis* grassland in northern China. *Sustainability (Switzerland)*, *8*(1), 1–10. https://doi.org/10.3390/su8010056

Cheng, S. H., Ahlroth, S., Onder, S., Shyamsundar, P., Garside, R., Kristjanson, P., McKinnon, M. C., & Miller, D. C. (2017). What is the evidence for the contribution of forests to poverty alleviation? A systematic map protocol. *Environmental Evidence*, *6*(1), 1–11. https:// doi. org/ 10. 1186/s13750-017-0088-9

Chothani, D. L., & Vaghasiya, H. U. (2011). A review on *Balanites aegyptiaca* Del (desert date): Phytochemical constituents, traditional uses, and pharmacological activity. *Pharmacognosy Reviews*, *5*(9), 55–62. https://doi.org/10.4103/0973-7847.79100

Dawson, I. K., Lengkeek, A., Weber, J. C., & Jamnadass, R. (2009). Managing genetic variation in tropical trees: Linking knowledge with action in agroforestry ecosystems for improved conservation and enhanced livelihoods. *Biodiversity and Conservation*, *18*(4), 969–986. https://doi.org/10.1007/s10531-008-9516-z

Deafalla, T. H. H., Dafa-Alla, D.A. M., & El-Abbas, M. M. (2014). *The importance of non wood forest products for rural livelihoods: The case of South Kordofan State, Sudan*. https://www.google.com

Degrande, A., Schreckenberg, K., Mbosso, C., Anegbeh, P., Okafor, V., & Kanmegne, J. (2006). Farmers' fruit tree-growing strategies in the humid forest zone of Cameroon and Nigeria. *Agroforestry Systems*, *67*(2), 159–175. https://doi.org/10.1007/s10457-005-2649-0

Deng, B., Tammeorg, P., Luukkanen, O., Helenius, J., & Starr, M. (2016). *Effects of Acacia seyal and biochar on soil properties and sorghum yield in agroforestry systems in South Sudan.* https://www.google.com

Derebe, Y., & Girma, Z. (2020). *Diet composition and preferences of Bohor reedbuck (Redunca redunca) in the compound of Alage College, Central Rift Valley of Ethiopia*. https://www.google.com

Djekota, C., Diouf, D., Sane, S., Mbaye, M. S., & Noba, K. (2014). Morphological characterization of shea tree (*Vitellaria paradoxa* subsp. paradoxa) populations in the region of Mandoul in Chad. *International Journal of Biodiversity and Conservation*, *6*(2), 184–193. https://doi.org/10.5897/ijbc2013.0662

Domene, M., Howe, H. F., Cruz-León, E., Jiménez-Rolland, R., Lozano-Huerta, C., & Martínez-Garza, C. (2017). *Seed to seedling transitions in successional habitats across a tropical landscape.* https://www.google.com

Dufour-Dror, J. M. (2007). Influence of cattle grazing on the density of oak seedlings and saplings in a Tabor oak forest in Israel. *Acta Oecologica*, *31*(2), 223–228. https:// doi. org/ 10. 1016/ j.actao.2006.11.003

Dunne, T., Western, D., & Dietrich, W. E. (2011). *Effects of cattle trampling on vegetation, infiltration, and erosion in a tropical rangeland*. https://www.google.com

Elagib, N. A., & Al-Saidi, M. (2020). Balancing the benefits from the water–energy–land–food nexus through agroforestry in the Sahel. *Science of the Total Environment*, *742*, 140509. https://doi.org/10.1016/j.scitotenv.2020.140509

Elbadawi, S. M. A., Ahmad, E. E. M., Mariod, A. A., & Mathäus, B. (2017). *Effects of thermal processing on physicochemical properties and oxidative stability of Balanities aegyptiaca* *kernels and extracted oil*. https://www.google.com

Elfeel, A. A., & Warrag, E. I. (2011). Uses and conservation status of *Balanites aegyptiaca* (L.) Del. (Hegleig Tree) in Sudan: Local people perspective. *Asian Journal of Agricultural Sciences*, *3*(4), 286–290.

Elfeel, A., Warrag, I., & Musnal, A. (2007). Response of *Balanites aegyptiaca* (L.) Del. Seedlings from Varied Geographical Source to Imposed Drought Stress. *Discovery Innovation*, *18*(4), 319–325.

Elfeel, A. A. (2010). Variability in *Balanites aegyptiaca var. aegyptiaca* seed kernel oil, protein and minerals contents between and within locations. *Agriculture and Biology Journal of North America*, *1*(2), 170–174. http://www.scihub.org/ABJNA

Elhadi, H. M., Ahmed, A. E., Adam, Y. O., & Eisa, M. A. (2014). Payment for Environmental Services (PES): A mechanism for adopting the agroforestry farming system among gum Arabic producers in Sudan. *International Journal of Development and Sustainability*, *3*(5), 1099–1112.

Elmekki, A. A. (2008). *Towrds community's involvement in integerated management in Dinder Biosphere Reserve, Sudan*. University of Khartoum. www.google.com

Elmoghraby, A. I., & Abdu, A. S. E. (1985). *The Dinder National Park study area (Central region)* (Issue 698).

Endale, Y., Derero, A., Argaw, M., & Muthuri, C. (2017). Farmland tree species diversity and spatial distribution pattern in semi-arid East Shewa, Ethiopia. *Forests Trees and Livelihoods*, *26*(3), 199–214. https://doi.org/10.1080/14728028.2016.1266971

Esquivel, M. J., Harvey, C. A., Finegan, B., Casanoves, F., & Skarpe, C. (2008). Effects of pasture management on the natural regeneration of neotropical trees. *Journal of Applied Ecology*, *45*(1), 371–380. https://doi.org/10.1111/j.1365-2664.2007.01411.x

Ezemokwe, G. C., Aguiyi, J. C., & Chollom, F. P. (2020). The Antibacterial activity of aqueous and ethanolic leaf extracts of Balanites aegyptiaca (l.) Del plant on some selected clinical human pathogens. *Journal of Advances in Microbiology*, *20*(10), 51–66. https:// doi. org/ 10.9734/ JAMB/2020/v20i1030290

Fadl, K. E. M., Mahmoud, S. E., & Hamad, Z. M. (2015). Farmers perceptions towards agroforestry systems in north and south Kordofan state, Sudan. *International Journal of Environment*, *4*(2), 53–67. https:// citeseerx. ist. psu. edu/ viewdoc/ download? doi=10. 1. 1. 883. 2659&rep=rep1&type=pdf

Fadl, K. E. M. (2015). *Balanites aegyptiaca* (L.): A Multipurpose Fruit Tree in Savanna Zone of Western Sudan. *International Journal of Environment*, *4*(1), 166–176.

Fahmi, K. M. M. (2017). *Climate, trees and agricultural practices: Implications for food security in the semi-arid zone of Sudan*. University of Helsinki.www.google.com

Fahmi, M. K. M., Mohamed, E. S., Kanninen, M., Luukkanen, O., Kalame, F. B., & Eltayeb, A. M. (2015). Determinants and constraints of integrating natural acacias into mechanised rain-fed agricultural schemes Sennar State, Sudan. *Geography Journal*, *80*(4), 555–567.

Fahmi, M. K. M., Dafa-Alla, D. A. M., Kanninen, M., & Luukkanen, O. (2018). Impact of agroforestry parklands on crop yield and income generation: Case study of rainfed farming in the semi-arid zone of Sudan. *Agroforestry Systems*, *92*(3), 785–800. https:// doi. org/ 10. 1007/ s10457-016-0048-3

Fakhry, A. M., Khazzan, M. M., & Aljedaani, G. S. (2020). Impact of disturbance on species diversity and composition of *Cyperus conglomeratus* plant community in southern Jeddah, Saudi. *Journal of King Saud University - Science*, *32*(1), 600–605. https:// doi. org/ 10. 1016/j. jksus.2018.09.003

FAO. (2015). *Sudan's Country Report contributing to the State of the World's Biodiversity for Food and Agriculture*. https://www.google.com

Folega, F., Gabriel, S., Zhang, C. Y., Hai, Z. X., Wala, K., Batawila, K., & Akpagana, K. (2011). Evaluation of agroforestry species in potential fallows of areas gazetted as protected areas in North-Togo. *African Journal of Agricultural Research*, *6*(12), 2828–2834.

Fraser, E. C., Kabzems, R., & Lieffers, V. J. (2001). Sheep grazing for vegetation management in the northern forests of British Columbia and Alberta. *Forestry Chronicle*, *77*(4), 713–719. https://doi.org/10.5558/tfc77713-4

Gamoun, M., Patton, B., & Hanchi, B. (2015). Assessment of vegetation response to grazing management in arid rangelands of southern Tunisia. *International Journal of Biodiversity*

Science, Ecosystem Services and Management, *11*(2), 106–113. https:// doi. org/ 10. 1080/ 21513732. 2014.998284

Gasmalla, H. B., Idris, A. M., Shinger, M. I., Qin, D., Shan, D., & Lu, X. (2016). *Balanites aegyptiaca* Oil Synthesized Iron Oxide Nanoparticles: Characterization and Antibacterial Activity. *Journal of Biomaterials and Nanobiotechnology*, *07*(03), 154–165. https:// doi. org/ 10. 4236/ jbnb.2016.73016

Gebeyehu, G., Soromessa, T., Bekele, T., & Teketay, D. (2019). Species composition, stand structure, and regeneration status of tree species in dry Afromontane forests of Awi Zone, northwestern Ethiopia. *Ecosystem Health and Sustainability*, *5*(1), 199–215. https:// doi. org/ 10. 1080/20964129.2019.1664938

Gebrehiwot, K., & Hundera, K. (2014). Species composition, plant community structure and natural regeneration status of Belete moist evergreen montane forest, Oromia regional state, Southwestern Ethiopia. *Momona Ethiopian Journal of Science*, *6*(1), 97. https:// doi. org/ 10. 4314/ mejs.v6i1.102417

Gebru, B. M., Wang, S. W., Kim, S. J., & Lee, W. K. (2019). Socio-ecological niche and factors affecting agroforestry practice adoption in different agroecologies of southern Tigray, Ethiopia. *Sustainability (Switzerland)*, *11*(13), 1–19. https://doi.org/10.3390/su11133729

Ghanbari, S., Sefidi, K., Kern, C. C., & Álvarez-Álvarez, P. (2021). *Population structure and regeneration status of woody plants in relation to the human Interventions, Arasbaran Biosphere Reserve, Iran.* https://www.google.com

Ghosh, M., & Devi, A. (2019). Assessment of crop growth, soil properties and crop yield in an upland acidic soil with inorganic fertilizer blended with organic amendments in summer rice cropping seasons. *International Journal of Recycling of Organic Waste in Agriculture*, *8*(s1), 1–9. https://doi.org/10.1007/s40093-019-0252-z

Gill, R. (2000). *The impact of deer on woodland biodiversity. Information Note - Forestry* https://www.google.com

Githae, E. W., Gachene, C. K. K., & Njoka, J. T. (2011). Soil physicochemical properties under *Acacia senegal* varieties in the dryland areas of Kenya. *African Journal of Plant Science*, *5*(8), 475–482. http://www.academicjournals.org/ajps

Grenier, M., Labrecque, S., Benoit, M., & Allard, M. (2008). *Accuracy assessment method for wetland object-based classification.* https://www.google.com

Guedje, N. M., Tchamou, N., & Lejoly, J. (2016). Tree response to bark harvest: the case of a medicinal species, *Garcinia lucida*, as source of raw materials for plant-based drug development. *Journal of Applied Biosciences*, *99*(1), 9476. https:// doi. org/ 10. 4314/jab. v99i1.13

Haarmeyer, D. H., Schumann, K., Bernhardt-Römermann, M., Wittig, R., Thiombiano, A., & Hahn, K. (2013). Human impact on population structure and fruit production of the socio-economically important tree *Lannea microcarpa* in Burkina Faso. *Agroforestry Systems*, *87*(6), 1363–1375. https://doi.org/10.1007/s10457-013-9644-7

Hammond, M. E., Pokorný, R., Okae-Anti, D., Gyedu, A., & Obeng, I. O. (2021). *The composition and diversity of natural regeneration of tree species in gaps under different intensities of forest disturbance*. https://www.google.com

Hanief, M., Bidalia, A., Meena, A., & Rao, K. S. (2016). Natural regeneration dynamics of dominant tree species along an altitudinal gradient in three different forest covers of Darhal watershed in north western Himalaya (Kashmir), India. *Tropical Plant Research*, *3*(2), 253–262.

Harlev, E., Nevo, E., Lansky, E. P., Lansky, S., & Bishayee, A. (2012). Anticancer attributes of desert plants: A review. *Anti-Cancer Drugs*, *23*(3), 255–271. https:// doi. org/ 10. 1097/ CAD. 0b013e32834f968c

Hasnain, M., Chen, J., Ahmed, N., Memon, S., Wang, L., Wang, Y., & Wang, P. (2020). The effects of fertilizer type and application time on soil properties, plant traits, yield and quality of tomato. *Sustainability (Switzerland)*, *12*(21), 1–14. https://doi.org/10.3390/su12219065

Hasoba, A. M. M., Siddig, A. A. H., & Yagoub, Y. E. (2020). Exploring tree diversity and stand structure of savanna woodlands in southeastern Sudan. *Journal of Arid Land*, *12*(4), 609–617. https://doi.org/10.1007/s40333-020-0076-8

Hassaballah, K. E. A. (2020). *Land degradation in the Dinder and Rahad Basins : Interactions between hydrology , morphology and ecohydrology in the Dinder nationalpark, Sudan*. Delft University of technology.www.google.com

Hassaballah, K, Mohamed, Y. A., & Uhlenbrook, S. (2016). *The Mayas wetlands of the Dinder and Rahad: Tributaries of the Blue Nile Basin (Sudan).* https://www.google.com

Hassaballah, K., Mohamed, Y., Omer, A., & Uhlenbrook, S. (2020). Modelling the Inundation and Morphology of the Seasonally Flooded Mayas Wetlands in the Dinder National Park-Sudan. *Environmental Processes*, *7*(3), 723–747. https://doi.org/10.1007/s40710-020-00444-5

Hassan, L. E. A., Dahham, S. S., Saghir, S. A. M., Mohammed, A. M. A., Eltayeb, N. M., Majid, A. M. S. A., & Majid, A. S. A. (2016). Chemotherapeutic potentials of the stem bark of *Balanite aegyptiaca* (L.) Delile: An antiangiogenic, antitumor and antioxidant agent. *BMC Complementary and Alternative Medicine*, *16*(1), 1–13. https://doi.org/10.1186/s12906-016-1369-5

Hassan, & Tag. (2017). *In-depth analysis of Drivers of Deforestation & Forest Degradation*. https://www.google.com

Hassanin, K. M. A., Mahmoud, M. O., Hassan, H. M., Abdel-Razik, A. R. H., Aziz, L. N., & Rateb, M. E. (2018). *Balanites aegyptiaca* ameliorates insulin secretion and decreases pancreatic apoptosis in diabetic rats: Role of SAPK/JNK pathway. *Biomedicine and Pharmacotherapy*, *102*(2017), 1084–1091. https://doi.org/10.1016/j.biopha.2018.03.167

Hawkins, H. J. (2017). A global assessment of Holistic Planned Grazing™ compared with season-long, continuous grazing: Meta-analysis findings. *African Journal of Range and Forage Science*, *34*(2), 65–75. https://doi.org/10.2989/10220119.2017.1358213

HCENR. (2004). *Management Plan for Dinder National Park Sudan. In Wildlife Conservation. Higher Council for Environment and Natural Resources*. https://www.google.com

Hernández, A. S. M., González, M. F. A., Martínez, V. A., Posadas, M. D. H., Aldrete, A., & Díaz, C. E. (2018). *Structure, richness and diversity of tree species in a tropical deciduous forest of Morelos.* https://www.google.com

Hernández, M. P. G., & Silva-Pando, F. J. (1996). Grazing effects of ungulates in a Galician oak forest (northwest Spain). *Forest Ecology and Management*, *88*, 65–70. https:// doi. org/ 10. 1016/ S0378-1127(96)03810-8

Heshmati, M., Gheitury, M., & Hosseini, M. (2018). Effects of runoff harvesting through semicircular bund on some soil characteristics. *Global Journal of Environmental Science and Management*, *4*(2), 207–216. https://doi.org/10.22034/gjesm.2018.04.02.008

Hofhansl, F., Chacón-Madrigal, E., Fuchslueger, L., Jenking, D., Morera-Beita, A., Plutzar, C., Silla, F., Andersen, K. M., Buchs, D. M., Dullinger, S., Fiedler, K., Franklin, O., Hietz, P., Huber, W., Quesada, C. A., Rammig, A., Schrodt, F., Vincent, A. G., Weissenhofer, A., & Wanek, W. (2020). Climatic and edaphic controls over tropical forest diversity and vegetation carbon storage. *Scientific Reports*, *10*(1), 1–11. https://doi.org/10.1038/s41598-020-61868-5

Hollingsworth, P. M., Dawson, I. K., Goodall-Copestake, W. P., Richardson, J. E., Weber, J. C., Montes, C. S., & Pennington, R. T. (2005). Do farmers reduce genetic diversity when they domesticate tropical trees? A case study from Amazonia. *Molecular Ecology*, *14*(2), 497–501. https://doi.org/10.1111/j.1365-294X.2005.02431.x

Ibrahim, E. M., & Hassan, T. T. (2015). Factors affecting natural regeneration and distribution of trees species in El-Nour natural forest reserve. *Journal of Natural Resources & Environmental Studies*, *3*(3), 16–21.

Ibrahim, E., Paity, B., Hassan, T., Idris, E., & Yousif, T. (2018). *Effect of tree species, tree variables and topography on CO_2 concentration in Badous riverine forest reserve – Blue Nile, Sudan*. *5*(1), 1–12.

Ibrahim, E., & Osman, E. (2014). Diameter at breast height-crown width prediction models for *Anogeissus leiocarpus* (DC.) Guill &Perr and *Combretum hartmannianum* Schweinf. *Journal of Forest Products & Industries, 3*(4), 191–197.

Ibrahim, E., Osman, E., & Idris, E. (2014). Modelling the relationship between crown width and diameter at breast height for naturally grown Terminalia tree species. *Journal of Natural Resources and Environmental Studies*, *6456*(6), 42–49.

Ibrahim, E., Osman, E., Idris, E., & Yousif, T. (2015). Linear and Non-Linear Regression Equations for Estimating the Crown Diameter of Three Sudanese Edible Trees. *Journal of Forest Products & Industries*, *4*(2), 44–52.

Ibrahim, G. A., Abdalla, N. I., & Fangama, I. M. (2015). Contributions of non-wood forest products to household food security and income generation in South Kordofan State, Sudan.

International Journal of Current Microbiology and Applied Sciences, *4*(6), 828–832. http://www.ijcmas.com/vol-4-6/Gammereldein A. Ibrahim, et al.pdf

Idrissa, B., Soumana, I., Issiaka, Y., Karimou, A., Mahamane, A., Mahamane, S., & Weber, J. (2018). Trend and Structure of Populations of *Balanites aegyptiaca* in Parkland Agroforestsin Western Niger. *Annual Research & Review in Biology*, *22*(4), 1–12. https:// doi. org/ 10. 9734/ arrb/ 2018/38650

IFAD. (2012). *Republic of The Sudan, Country programme Evaluation.* https://www.google.com

Isaac, M. E., Harmand, J., Lesueur, D., & Lelon, J. (2011). Tree age and soil phosphorus conditions influence N_2 -fixation rates and soil N dynamics in natural populations of *Acacia senegal*. *Forest Ecology and Management*, *261*(3), 582–588. https:// doi. org/ 10. 1016/j. foreco. 2010.11.011

Jevon, F. V., Record, S., Grady, J., Lang, A. K., Orwig, D. A., Ayres, M. P., & Matthes, J. H. (2020). *Seedling survival declines with increasing conspecific density in a common temperate tree.* https://www.google.com

Ji, Y., Ranjan, R., & Truong, C. (2017). Determinants of illegal logging in Indonesia: An empirical analysis for the period 1996–2010. *Journal of Sustainable Forestry*, *37*(2), 197–220. https://doi.org/10.1080/10549811.2017.1369436

Joel, E. (2018). *Productivity and conservation practices for Balanites aegyptiaca (Desert date) in Napak woodlands*. Makerere.

John, E., Bunting, P., Hardy, A., Roberts, O., Giliba, R., & Silayo, D. S. (2020). Modelling the impact of climate change on Tanzanian forests. *Diversity and Distributions*, *26*(12), 1663–1686. https://doi.org/10.1111/ddi.13152

Jurgensen, M. F., Harvey, A. E., Graham, R. T., Page-Dumroese, D. S., Tonn, J. R., Larsen, M. J., & Jain, T. B. (1997). Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of Inland northwest forests. *Forest Science*, *43*(2), 234–251.

Kacholi, D. S. (2014). Analysis of Structure and Diversity of the Kilengwe Forest in the Morogoro Region, Tanzania. *International Journal of Biodiversity*, *2014*(ii), 1–8. https:// doi. org/ 10. 1155/2014/516840

Kgosikoma, O. E., Mojeremane, W., & Harvie, B. A. (2013). Grazing management systems and their effects on savanna ecosystem dynamics: A review. *Journal of Ecology and The Natural Environment*, *5*(6), 88–94. https://doi.org/10.5897/jene2013.0364

Khamis, G., Saleh, A. M., Habeeb, T. H., Hozzein, W. N., Wadaan, M. A. M., Papenbrock, J., & AbdElgawad, H. (2020). Provenance effect on bioactive phytochemicals and nutritional and health benefits of the desert date *Balanites aegyptiaca*. *Journal of Food Biochemistry*, *44*(6), 1–13. https://doi.org/10.1111/jfbc.13229

Khamis, G., Winkelmann, T., Schaarschmidt, F., & Papenbrock, J. (2016). Establishment of an in vitro propagation and transformation system of *Balanites aegyptiaca*. *Plant Cell, Tissue and Organ Culture*, *125*(3), 457–470. https://doi.org/10.1007/s11240-016-0961-1

Khamis, M. A., & Abdalla, E. A. (2017). *Non-Wood Forest Products (NWFPs) and Their Role in Rural Development and Poverty Reduction in North Darfur State, Sudan*. *8*(3), 162–170.

Khatoon, R., Jahan, N., Ahmed, S., & Shahzad, A. (2013). Antifungal activity of aerial parts as well as in vitro raised calli of the medicinal plant, *Balanites aegyptiaca* Del. *African Journal of Plant Science*, *7*(10), 476–481. https://doi.org/10.5897/AJPS2013.1058

Kikoti, I., & Mligo, C. (2015). Impacts of livestock grazing on plant species composition in montane forests on the northern slope of Mount Kilimanjaro, Tanzania. *International Journal of Biodiversity Science, Ecosystem Services and Management*, *11*(2), 114–127. https://doi.org/10.1080/21513732.2015.1031179

Kikoti, I., Mligo, C., & Kilemo, D. (2015). The Impact of Grazing on Plant Natural Regeneration in Northern Slopes of Mount Kilimanjaro, Tanzania. *Open Journal of Ecology*, *05*(06), 266–273. https://doi.org/10.4236/oje.2015.56021

Kim, Y., & Eltahir, E. A. B. (2004). Role of topography in facilitating coexistence of trees and grasses within savannas. *Water Resources Research*, *40*(7), 1–13. https:// doi. org/ 10. 1029/ 2003WR002578

Kimaro, J., & Lulandala, L. (2013). Human influences on tree diversity and composition of a coastal forest ecosystem: The case of Ngumburuni forest reserve, Rufiji, Tanzania. *International Journal of Forestry Research*, *2013*, 1–7. https://doi.org/10.1155/2013/305874

Kingazi, N., Petro, R., Mbwambo, J. R., & Munishi, L. K. (2020). Performance of *Pinus patula* in areas invaded by *Acacia mearnsii* in Sao Hill forest plantation, Southern Tanzania. *Journal of Sustainable Forestry*, *00*(00), 1–10. https://doi.org/10.1080/10549811.2020.1788952

Kochare, T., Tamir, B., & Kechero, Y. (2018). Palatability and animal preferences of plants in small and fragmented land holdings: The case of Wolayta Zone, Southern Ethiopia. *Agricultural Research & Technology: Open Access Journal*, *14*(3). https:// doi. org/ 10.19080/artoaj.2018.14.555922

Kosmas, C., Detsis, V., Karamesouti, M., Kounalaki, K., Vassiliou, P., & Salvati, L. (2015). Exploring long-term impact of grazing management on land degradation in the socio-ecological system of Asteroussia Mountains, Greece. *Land*, *4*(3), 541–559. https:// doi. org/ 10.3390/ land4030541

Krzic, M., Newman, R. F., Trethewey, C., Bulmer, C. E., & Chapman, B. K. (2006). Cattle grazing effects on plant species composition and soil compaction on rehabilitated forest landings in central interior British Columbia. *Journal of Soil and Water Conservation*, *61*(3), 137–144.

Kutnar, L., Nagel, T. A., & Kermavnar, J. (2019). Effects of disturbance on understory vegetation across slovenian forest ecosystems. *Forests*, *10*(11), 1–16. https:// doi. org/ 10.3390/ F10111048

Lacerda, A. E. B., & Kellermann, B. (2019). What is the Long-Term Effect of Bamboo Dominance on Adult Trees in the Araucaria Forest? A Comparative Analysis between Two Successional Stages in Southern Brazil. *Diversity*, *11*(9), 165. https://doi.org/10.3390/d11090165

Lamien, N., Tigabu, M., Guinko, S., & Oden, P. C. (2007). Variations in dendrometric and fruiting characters of *Vitellaria paradoxa* populations and multivariate models for estimation of fruit yield. *Agroforestry Systems*, *69*(1), 1–11. https://doi.org/10.1007/s10457-006-9013-x

Larson, S., Barry, S., & Bush, L. (2015). *Cattle, Sheep, Goats, and Horses: What's the Difference for Working Rangelands? University of California, Agriculture and Natural Resources, 8524(July)*. https://doi.org/10.3733/ucanr.8524

Lempesi, A., Eleftheriadou, A., Delivasi, Z., Psyllidou, A., Korakis, G., & Kyriazopoulos, A. P. (2017). Effects of grazing intensity on the regeneration of woody species in an oak woodland. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *45*(2), 597–601. https:// doi.org/10.15835/nbha45210908

Li, S., Yu, F., Werger, M. J. A., Dong, M., Ramula, S., & Zuidema, P. A. (2013). Understanding the effects of a new grazing policy: The impact of seasonal grazing on shrub demography in the Inner Mongolian steppe. *Journal of Applied Ecology*, *50*, 1377–1386. https:// doi. org/ 10. 1111/ 1365-2664.12159

Ligate, E. J., Wu, C., & Chen, C. (2019). Investigation of tropical coastal forest regeneration after farming and livestock grazing exclusion. *Journal of Forestry Research*, *30*(5), 1873–1884. https://doi.org/10.1007/s11676-018-0792-5

Listopad, C. M. C. S., Köbel, M., Príncipe, A., Gonçalves, P., & Branquinho, C. (2018). *The effect of grazing exclusion over time on structure, biodiversity, and regeneration of high nature value farmland ecosystems in Europe.* https://www.google.com

Lockett, C. T., Calvert, C. C., & Grivetti, L. E. (2000). Energy and micronutrient composition of dietary and medicinal wild plants consumed during drought. Study of rural Fulani, Northeastern Nigeria. *International Journal of Food Sciences and Nutrition*, *51*(3), 195–208. https://doi.org/10.1080/09637480050029700

Lompo, O., Lykke, A. M., Lankoandé, B., & Ouédraogo, A. (2018). Influence of climate on fruit production of the yellow plum, *Ximenia americana*, in Burkina Faso, West Africa. *Journal of Horticulture and Forestry*, *10*(4), 36–42. https://doi.org/10.5897/jhf2017.0517

Lopez-Sanchez, A., Sdhroeder, J., Roig, S., Sobral, M., & Dirzo, R. (2014). Effects of cattle management on oak regeneration in northern Californian Mediterranean oak woodlands. *PLoS ONE*, *9*(8), 1–9. https://doi.org/10.1371/journal.pone.0105472

Luginbuhl, J., Mueller, J. P., Green, T. J., Chamblee, S. D., & Glennon, M. H. (2010). *Grazing and Browsing Behavior, Grazing Management, Forage Evaluation and Goat Performance: Strategies to Enhance Meat Goat Production in North Carolina.* https://www.google.com

Magid, T. D. A., El Tiab, A. A., & Siddig, E. N. A. (2014). Participatory management of natural forests in Sudan: Case of El Rawashda forest reserve; Gedaref State. *Journal of Forest*

Products & Industries, *3*(2014), 124–129.

Mahgoub, A. A. M. (2014). *Changes in Vegetation Cover and Impacts of Human Population in Dinder National Park, Sudan During the Period from 1972 to 2013*. https://www.google.com

Manandhar, S., Luitel, S., & Dahal, R. K. (2019). *In Vitro Antimicrobial Activity of Some Medicinal Plants against Human Pathogenic Bacteria*. https://www.google.com

Manji, A. J., Sarah, E. E., & Modibbo, U. U. (2013). Studies on the potentials of *Balanites aegyptiaca* seed oil as raw material for the production of liquid cleansing agents. *International Journal of Physical Sciences*, *8*(33), 1655–1660. https://doi.org/10.5897/IJPS07.049

Marone, D., Poirier, V., Coyea, M., Olivier, A., & Munson, A. D. (2017). Carbon storage in agroforestry systems in the semi-arid zone of Niayes, Senegal. *Agroforestry Systems*, *91*(5), 941–954. https://doi.org/10.1007/s10457-016-9969-0

Martinelli, L. A., Almeida, S., Brown, I. F., Moreira, M. Z., Victoria, R. L., Filoso, S., Ferreira, A. C., & Thomas, W. W. (2000). Variation in nutrient distribution and potential nutrient losses by selective logging in a humid tropical forest of Rondonia, Brazil1. *Biotropica*, *32*(4a), 597–613.

Maruod, M. E., Ibrahim, S. M., Mahmoud, T. E., & Hassan, A. A. A. (2014). Non-Timber Forest Products (NTFPs): Opportunities and Constrains to Achieve Food Security and Livelihood in western sector localities of South Kordofan state , Sudan. *International Journal of Farming and Allied Sciences*, *2006*, 1248–1255.

Maua, J. O., Tsingalia, H. M., Cheboiwo, J., & Odee, D. (2020). Population structure and regeneration status of woody species in a remnant tropical forest: A case study of South Nandi forest, Kenya. *Global Ecology and Conservation*, *21*, e00820. https:// doi. org/ 10. 1016/ j. gecco. 2019.e00820

McEvoy, P. M., McAdam, J. H., Mosquera-Losada, M. R., & Rigueiro-Rodríguez, A. (2006). Tree regeneration and sapling damage of pedunculate oak *Quercus robur* in a grazed forest in Galicia, NW Spain: A comparison of continuous and rotational grazing systems. *Agroforestry Systems*, *66*(2), 85–92. https://doi.org/10.1007/s10457-005-2916-0

Megaze, A., Belay, G., & Balakrishnan, M. (2012). Population structure and ecology of the African buffalo (*Syncerus caffer* Sparrman, 1779) in Chebera Churchura National Park, Ethiopia. *African Journal of Ecology*, *51*(3), 393–401. https://doi.org/10.1111/aje.12049

Mekuria, W., & Aynekulu, E. (2013). Exclosure land management for restoration of the soils in degraded communal grazing lands in northern Ethiopia. *Land Degradation and Development*, *24*(6), 528–538. https://doi.org/10.1002/ldr.1146

Meng, X. (2013). Scalable simple random sampling and stratified sampling. *30th International Conference on Machine Learning, ICML 2013*.www.google

Missanjo, E., & Kamanga-thole, G. (2014). Impact of site disturbances from harvesting and logging on soil physical properties and *Pinus kesiya* Tree Growth. *International Scholarly Research Notices*, *2014*, 1–7.

Missanjo, E., Ndalowa, D., & Malinga, D. (2015). Stand age and diameter class effect on seed production of *Pinus kesiya Royle* ex Gordon grown in Malawi. *Scholars Academic Journal of Biosciences*, *3*(2B), 173–177.

Mohammed, A. N. E., & Hashim, I. M. (2015). Illegal and patrolling activities in Dinder National Park from 1959-2010. *Journal of Natural Resources & Environmental Studies*, *6456*(11), 22–32.

Mohammed, E. M., Hammed, A., Minnick, T., Ndakidemi, P., & Treydte, A. (2021). *Livestock browsing threatens the survival of Balanites aegyptiaca seedlings and saplings: a case study from Dinder Biosphere Reserve, Sudan*. www.google.com

Mohammed, E. M. I., Elhag, A. M. H., Ndakidemi, P. A., & Treydte, A. C. (2021). Anthropogenic pressure on tree species diversity, composition, and growth of *Balanites aegyptiaca* in Dinder Biosphere Reserve, Sudan. *Plants*, *10*(483), 1–18.

Mukhtar, Y., Abdu, K., & Maigar, A. K. (2017). Efficacy of *Anogeissus leiocarpus* (DC.) as potential therapeutic agent against Trypanosomiasis diseases : A review. *Iternational Journal of Health and Pharmaceutical Research*, *3*(3), 1–9.

Mukul, S. A., Rashid, A. Z. M. M., Uddin, M. B., & Khan, N. A. (2016). Role of non-timber forest products in sustaining forest-based livelihoods and rural households' resilience capacity in and around protected area: A Bangladesh study†. *Journal of Environmental*

Planning and Management, *59*(4), 628–642. https://doi.org/10.1080/09640568.2015.1035774

Müller, K., Dickhoefer, U., Lin, L., Glindemann, T., Wang, C., Schönbach, P., Wan, H. W., Schiborra, A., Tas, B. M., Gierus, M., Taube, F., & Susenbeth, A. (2014). Impact of grazing intensity on herbage quality, feed intake and live weight gain of sheep grazing on the steppe of Inner Mongolia. *Journal of Agricultural Science*, *152*(1), 153–165. https:// doi. org/ 10. 1017/ S0021859613000221

Murthy, H. N., Yadav, G. G., Dewir, Y. H., & Ibrahim, A. (2021). Phytochemicals and biological activity of desert date (*Balanites aegyptiaca* (L.) delile). *Plants*, *10*(1), 1–22. https:// doi. org/ 10. 3390/plants10010032

Mwakosya, J., & Mligo, C. (2014). The impacts of anthropogenic activities on the vegetation communities and structure in the western part of Rungwe forest reserve, Tanzania. *Tanzania Journal of Science*, *40*(1), 60–78.

Mysterud, A. (2006). The concept of overgrazing and its role in management of large herbivores. *Wildlife Biology*, *12*(2), 129–141. https:// doi. org/ 10. 2981/ 0909- 6396 (2006) 12 [129: TCOOAI] 2. 0.CO;2

Nacoulma, B. M. I., Lykke, A. M., Traoré, S., Sinsin, B., & Thiombiano, A. (2016). Impact of bark and foliage harvesting on fruit production of the multipurpose tree *Afzelia africana* in Burkina Faso (West Africa). *Agroforestry Systems*, *91*(3), 565–576. https://doi.org/10.1007/s10457-016-9960-9

Nakajima, A., Masaki, T., Koike, S., Yamazaki, K., & Kaji, K. (2015). Estimation of tree crop size across multiple taxa: Generalization of a visual survey method. *Open Journal of Forestry*, *05*(07), 651–661. https://doi.org/10.4236/ojf.2015.57057

Ndoye, M., Diallo, I., & Gassama-Dia, Y. K. (2004). Reproductive biology in *Balanites aegyptiaca* (L.) Del., a semi-arid forest tree. *African Journal of Biotechnology*, *3*(1), 40–46.

Neelo, J., Teketay, D., Kashe, K., & Masamba, W. (2015). Stand structure, diversity and regeneration status of woody species in open and exclosed dry woodland sites around Molapo farming areas of the Okavango Delta, Northeastern Botswana. *Open Journal of Forestry*, *05*(04), 313–328. https://doi.org/10.4236/ojf.2015.54027

Negussie, A., Aerts, R., Gebrehiwot, K., & Muys, B. (2008). Seedling mortality causes recruitment limitation of *Boswellia papyrifera* in northern Ethiopia. *Journal of Arid Environments*, *72*(4), 378–383. https://doi.org/10.1016/j.jaridenv.2007.06.009

Neya, T., Neya, O., & Abunyewa, A. A. (2019). *Agroforestry parkland profiles in three climatic zones of Burkina Faso*. https://www.google.com

Niass, O., Sarr, S. O., Diop, A., Diop, A., & Diop, Y. M. (2016). *Journal of Chemical, Biological and Physical Sciences In Vitro Assessment of Antimicrobial Activity of Combretum Glutinosum Leaves Extracts* (*Combretaceae*), *6*(2), 603–608.

Nndwammbi, M., Ligavha-Mbelengwa, M. H., Anokwuru, C. P., & Ramaite, I. D. I. (2018). The effects of seasonal debarking on physical structure, polyphenolic content and antibacterial and antioxidant activities of *Sclerocarya birrea* in the Nylsvley nature reserve. *South African Journal of Botany*, *118*(2018), 138–143. https://doi.org/10.1016/j.sajb.2018.06.018

Nyong, W. U., Adedeji, A. A., Afolayan, J. O., & Alomaja, J. (2019). *Physical and mechanical properties of Nigerian-grown African Birch* (*Anogeissus leiocarpus*) *Timber*. *March*. https://www.google.com

Ogala, H., Elinge, C., Wawata, I., Adegoke, A., Muhammad, A., & Ige, A. (2018). Extraction and Physicochemical Analysis of Desert Date (*Balanites aegyptiaca*) Seed Oil. *International Journal of Advanced Academic Research (Sciences*, *Technology & Engineering)*, *4*(4), 1–12.

Ogunwusi, A. A., Onwualu, A., & Ogunsanwo, O. (2013). Comparative analysis of wood properties of *Afzelia africana* and *Anogeissus leiocarpus* Growing in Nigeria. *Chemistry and Materials Research*, *3*(3), 8–13.

Okia, C. A. (2013). Nutritional value of commonly consumed desert date tree products. *Nutritional Value of Commonly Consumed Desert Date Tree Products.*, *21*(1), 657–668. https:// doi. org/ 10. 4314/acsj.v21i1

Okia, C. A. (2013). *Balanites aegyptiaca*: *A resource for Improving Nutrition and Income of Dryland Communities in Uganda [Bangor University]*. https://www.google.com

Omar, G., & Muhammad, I. (2016). Comparative study of soil physico-chemical properties under *Acacia senegal* in three different plantations in Maifari, Jigawa state, Nigeria. *Bayero*

Journal of Pure and Applied Sciences, *8*(2), 111–116. https://doi.org/10.4314/bajopas.v8i2.19

Osem, Y., Fogel, T., Moshe, Y., Ashkenazi, M., & Brant, S. (2017). *Understory structure and function following release from cattle grazing and overstory thinning in Mediterranean conifer plantations.* https://www.google.com

Osman, E. M. H., & Idris, E. Z. A. (2012). Species Dynamics and Potential Disturbances in El Nour Natural Forest Reserve, Sudan. *Journal of Forest Products & Industries*, *1*(2), 10–20.

Ouédraogo, S., Bondé, L., Ouédraogo, O., Ouédraogo, A., Thiombiano, A., & Boussim, I. J. (2019). To what extent do tree size, climate and land use influence the fruit production of *Balanites aegyptiaca* (L) Delile in tropical areas (Burkina Faso)? *International Journal of Fruit Science*, *20*(3), 282–299. https://doi.org/10.1080/15538362.2019.1619216

Panagopoulos, Y., Dimitriou, E., & Skoulikidis, N. (2019). Vulnerability of a Notheast Mediterranean Island to Soil Loss. Can Grazing Management Mitigate Erosion ? *Water*, *11*(1491), 1–20.

Papadopoulos, A., Pantera, A., Fotiadis, G., Papaspyropoulos, K., Mantzanas, K., & Papanastasis, V. P. (2017). *Effects of grazing and understorey clearing on regeneration of a valonia oak silvopastoral system in Western Greece.* https://www.google.com

Pfeifer, M., Burgess, N. D., Swetnam, R. D., Platts, P. J., Willcock, S., & Marchant, R. (2012). Protected areas: Mixed success in conserving East Africa's evergreen forests. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0039337

Piabuo, S. M., Minang, P. A., Tieguhong, C. J., Foundjem-Tita, D., & Nghobuoche, F. (2021). *Illegal logging, governance effectiveness and carbon dioxide emission in the timber-producing countries of Congo Basin and Asia.* https://www.google.com

Pirzadeh, H., Shanian, S., Hamou-Lhadj, A., Alawneh, L., & Shafiee, A. (2013). *Stratified sampling of execution traces: Execution phases serving as strata*. https://www.google.com

Poudel, S., Karki, U., Karki, Y., & Tillman, A. (2019). *Diurnal behavior of Kiko wethers in southern-pine silvopastures planted with warm-season forages.* https://www.google.com

Powell, B., Ickowitz, A., McMullin, S., Jamnadass, R., Padoch, C., Pinedo-Vasquez, M., & Sunderland, T. (2013). *The role of forests, trees and wild biodiversity for nutrition-sensitive food systems and landscapes. ICN2 Second International Conference on Nutrition, Better Nutrition Better Lives.* FAO and WHO. https://doi.org/10.1097/00007611-196209000-00025

Raddad, E. Y., Luukkanen, O., Salih, A. A., Kaarakka, V., & Elfadl, M. A. (2006). Productivity and nutrient cycling in young *Acacia senegal* farming systems on Vertisol in the Blue Nile region, Sudan. *Agroforestry Systems*, *68*, 193–207. https://doi.org/10.1007/s10457-006-9009-6

Rahim, A. H., van Ierland, E. C., & Wesseler, J. (2007). Economic incentives for abandoning or expanding gum arabic production in Sudan. *Forest Policy and Economics, 10*(1–2), 36–47. https://doi.org/10.1016/j.forpol.2007.02.002

Rahman, I. U., Ijaz, F., Afzal, A., Iqbal, Z., Ali, N., & Khan, S. M. (2016). *Contributions to the phytotherapies of digestive disorders: Traditional knowledge and cultural drivers of Manoor Valley, Northern Pakistan.* https://www.google.com

Ranaivoson, T., Brinkmann, K., Rakouth, B., & Buerkert, A. (2015). Distribution, biomass and local importance of tamarind trees in south-western Madagascar. *Global Ecology and Conservation*, *4*, 14–25. https://doi.org/10.1016/j.gecco.2015.05.004

Ravenel, R. M. (2004). Community-Based Logging and De Facto Decentralization. *Journal of Sustainable Forestry*, *19*(1–3), 213–237. https://doi.org/10.1300/j091v19n01_10

Reboredo, F. (2013). Socio-economic, environmental, and governance impacts of illegal logging. *Environment Systems and Decisions*, *33*(2), 295–304. https://doi.org/10.1007/s10669-013-9444-7

Reuter, K. E., Sewall, B. J., & Di Minin, E. (2018). Drivers of present and lifetime natural resource use in a tropical biodiversity hotspot. *Animal Conservation*, *21*(2), 127–136. https:// doi.org/ 10. 1111/acv.12355

Riba, M. (1998). *Effects of intensity and frequency of crown damage on resprouting of Erica arborea L. (Ericaceae).* https://www.google.com

Riginos, C., Grace, J. B., Augustine, D. J., & Young, T. P. (2009). Local versus landscape-scale effects of savanna trees on grasses. *Journal of Ecology*, *97*(6), 1337–1345. https:// doi. org/ 10. 1111/j.1365-2745.2009.01563.x

Saaid, A. A., Mohammed, A. E., Sara, A. M., & Samia, H. A. (2019). *Strobiloestrus clarkii* in *Redunca redunca* at Dinder National Park. *Asian Journal of Applied Sciences*, *12*(1), 7–14. https://doi.org/10.3923/ajaps.2019.7.14

Sagna, M. B., Niang, K. S., Guisse, A., & Goffner, D. (2014). *Balanites aegyptiaca* (L.) Delile: Geographical distribution and ethnobotanical knowledge by local populations in the ferlo (North Senegal). *Biotechnology, Agronomy and Society and Environment*, *18*(4), 503–511.

Sales-Baptista, E., d'Abreu, M. C., & Ferraz-de-Oliveira, M. I. (2016). Overgrazing in the Montado? The need for monitoring grazing pressure at paddock scale. *Agroforestry Systems*, *90*(1), 57–68. https://doi.org/10.1007/s10457-014-9785-3

Salih, E. Y. A., Kanninen, M., Sipi, M., Luukkanen, O., Hiltunen, R., Vuorela, H., Julkunen-Tiitto, R., & Fyhrquist, P. (2017). Tannins, flavonoids and stilbenes in extracts of African savanna woodland trees *Terminalia brownii*, *Terminalia laxiflora* and *Anogeissus leiocarpus* showing promising antibacterial potential. *South African Journal of Botany*, *108*, 370–386. https://doi.org/10.1016/j.sajb.2016.08.020

Sanon, H. O., Kaboré-Zoungrana, C., & Ledin, I. (2007). Behaviour of goats, sheep and cattle and their selection of browse species on natural pasture in a Sahelian area. *Small Ruminant Research*, *67*(1), 64–74. https://doi.org/10.1016/j.smallrumres.2005.09.025

Sawadogo, W. R., Luo, Y., Elkington, B., He, T., Wang, C., & Yuan, C. (2020). Assessment of the Anti-proliferative Effect and Preliminary Analysis of Cell Cycle Arrest and Pro-apoptotic Effects of *Balanites aegyptiaca* (L .) Delile on Colorectal Cancer Cells HCT-116 and HT-29. *Journal of Pharmaceutical International*, *32*(15), 9–21. https:// doi. org/ 10. 9734/ JPRI/ 2020/ v32i1530619

Scholten, T., Goebes, P., Kuhn, P., Seitz, S., Assmann, T., Bauhus, J., Bruelheide, H., Buscot, F., Erfmeier, A., Fischer, M., Hartle, W., He, J. S., Ma, K., Niklaus, P. A., Scherer-Lorenzen, M., Schmid, B., Shi, X., Song, Z., Von Oheimb, G., … Schmidt, K. (2017). On the combined effect of soil fertility and topography on tree growth in subtropical forest ecosystems'a study from SE China. *Journal of Plant Ecology*, *10*(1), 111–127. https://doi.org/10.1093/jpe/rtw065

Seth, M. K. (2004). Trees and their economic importance. *The Botanical Review*, *69*(4), 321–376. https://doi.org/10.1663/0006-8101(2004)069[0321:TATEI]2.0.CO;2

Shackleton, C. (2002). Growth and fruit production of *Sclerocarya birrea* in the South African lowveld. *Agroforestry Systems*, *55*(3), 175–180. https://doi.org/10.1023/A:1020579213024

Sher, H., Ahmed, A., Eleyemeni, M., Fazl-i-Hadi, S., & Sher, H. (2010). Impact of the Nomadic Grazing on Medicinal Plants Diversity in Miandam, Swat-Pakistan. *American-Eurasian Journal of Sustainable Agriculture*, *4*(2), 152–159.

Siddique, I., & Anis, M. (2009). Direct plant regeneration from nodal explants of *Balanites aegyptiaca* L. (Del.): A valuable medicinal tree. *New Forests*, *37*(1), 53–62. https:// doi. org/ 10. 1007/s11056-008-9110-y

Sigaye, M., Nigussei, A., Lulie, B., Mekuria, R., & Kebede, K. (2020). Effects of organic and inorganic fertilizers on soil properties, yield and yield components of Maize (*Zea mays* L.) grown on an Andisols at Hawassa Zuria , Ethiopia. *Advances in Applied Science Research*, *11*(4-9), 1–8.

Simons, N. K., Felipe-Lucia, M. R., Schall, P., Ammer, C., Bauhus, J., Blüthgen, N., Boch, S., Buscot, F., Fischer, M., Goldmann, K., Gossner, M. M., Hänsel, F., Jung, K., Manning, P., Nauss, T., Oelmann, Y., Pena, R., Polle, A., Renner, S. C., … Weisser, W. W. (2021). National forest inventories capture the multifunctionality of managed forests in Germany. *Forest Ecosystems*, *8*(5), 1-19. https://doi.org/10.1186/s40663-021-00280-5

Singh, A. P., Das, S., Mazumder, A., Kumar, M., & Gautam, N. (2017). A prespective review on a novel plant *Balanites aegyptiaca* (linn.). *Journal of Pharmaceutical and Biological Sciences*, *5*(6), 273–277.

Singh, K. P., & Kushwaha, C. P. (2006). Diversity of flowering and fruiting phenology of trees in a tropical deciduous forest in India. *Annals of Botany*, *97*, 265–276. https:// doi. org/ 10. 1093/ aob/mcj028

Singh, S., Malik, Z. A., & Sharma, C. M. (2016). Tree species richness, diversity, and regeneration status in different oak (*Quercus spp*.) dominated forests of Garhwal Himalaya, India. *Journal of Asia-Pacific Biodiversity*, *9*(3), 293–300. https://doi.org/10.1016/j.japb.2016.06.002

Snook, L. K., Cámara-Cabrales, L., & Kelty, M. J. (2005). Six years of fruit production by mahogany trees (*Swietenia macrophylla* King): Patterns of variation and implications for sustainability. *Forest Ecology and Management*, *206*(1–3), 221–235. https:// doi. org/ 10. 1016/j.foreco.2004.11.003

Solar, R. R., Barlow, J., Andersen, A. N., Schoereder, J. H., Berenguer, E., Ferreira, J. N., & Gardner, T. A. (2016). Biodiversity consequences of land-use change and forest disturbance in the Amazon: A multi-scale assessment using ant communities. *Biological Conservation*, *197*, 98–107. https://doi.org/10.1016/j.biocon.2016.03.005

Ssegawa, P., & Kasenene, J. M. (2007). Medicinal plant diversity and uses in the Sango bay area, Southern Uganda. *Journal of Ethnopharmacology*, 25 (113), 521-40. https:// doi. org/ 10. 1016/ j. jep.2007.07.014

Storch, F., Dormann, C. F., & Bauhus, J. (2018). Quantifying forest structural diversity based on large-scale inventory data: A new approach to support biodiversity monitoring. *Forest Ecosystems*, *5*(1), 1–14. https://doi.org/10.1186/s40663-018-0151-1

Sukhbaatar, G., Baatarbileg, N., Battulga, P., Batsaikhan, G., Khishigjargal, M., Batchuluun, T., & Gradel, A. (2019). Which selective logging intensity is most suitable for the maintenance of soil properties and the promotion of natural regeneration in highly continental scots pine forests? - Results 19 years after harvest operations in Mongolia. *Forests*, *10*(141), 1–21. https://doi.org/10.3390/f10020141

Suleiman, M. S., Wasonga, V. O., Mbau, J. S., Suleiman, A., & Elhadi, Y. A. (2017). Non-timber forest products and their contribution to households income around Falgore Game Reserve in Kano, Nigeria. *Ecological Processes*, *6*(1), 1-14. https://doi.org/10.1186/s13717-017-0090-8

Tesfaye, A. (2015). Balanites (*Balanites aegyptiaca*) Del., Multipurpose Tree a Prospective Review. *International Journal of Modern Chemistry and Applied Science*, *3*(78), 189–194.

Toledo, M., Poorter, L., Peña-Claros, M., Alarcón, A., Balcázar, J., Leaño, C., Licona, J. C., Llanque, O., Vroomans, V., Zuidema, P., & Bongers, F. (2011). Climate is a stronger driver of tree and forest growth rates than soil and disturbance. *Journal of Ecology*, *99*(1), 254–264. https://doi.org/10.1111/j.1365-2745.2010.01741.x

Treydte, A. C., Grant, C. C., & Jeltsch, F. (2009). Tree size and herbivory determine below-canopy grass quality and species composition in savannahs. *Biodiversity and Conservation*, *18*(14), 3989–4002. https://doi.org/10.1007/s10531-009-9694-3

Treydte, A. C., Heitkönig, I. M. A., Prins, H. H. T., & Ludwig, F. (2007). Trees improve grass quality for herbivores in African savannas. *Perspectives in Plant Ecology, Evolution and Systematics*, 4, 197 - 205. https://doi.org/10.1016/j.ppees.2007.03.001

Treydte, C. A., Bernasconi, M. S., Kreuzer, M., & Edwards, J. P. (2006). Diet of the common warthog (*Phacochoerus Africanus*) on Former Cattle Grounds in a Tanzanian Savanna. *Journal of Mammalogy*, *87*(5), 889–898.

Tripathi, O. P., & Tripathi, R. S. (2010). Community composition, structure and management of subtropical vegetation of forests in Meghalaya State, northeast India. *International Journal of Biodiversity Science, Ecosystem Services and Management*, *6*(3–4), 157–163. https://doi.org/10.1080/21513732.2010.539987

Tripathi, O. P., Upadhaya, K., Tripathi, R. S., & Pandey, H. N. (2010). Diversity, Dominance and Population Structure of Tree Species along Fragment-Size Gradient of a Subtropical Humid Forest of Northeast India. *Research Journal of Environmental and Earth Sciences*, *2*(2), 97–105.

Truong, T. H. H., & Marschner, P. (2018). Addition of residues with different C/N ratio in soil over time individually or as mixes-effect on nutrient availability and microbial biomass depends on amendment rate and frequency. *Journal of Soil Science and Plant Nutrition*, *18*(4), 1173–1186. https://doi.org/10.4067/s0718-95162018005003401

Tsegu, E. (2019). The role of *Faidherbia albida* tree species in parkland agroforestry and its management in Ethiopia. *Journal of Horticulture and Forestry*, *11*(3), 42–47. https:// doi. org/ 10. 5897/jhf2018.0570

Tula, M. Y., Danchal, T. B., Iruolaje, F. O., & Onyeje, G. A. (2014). Studies on Phytochemical Constituents and Antibacterial Potentials of Extracts of *Balanites aegyptiaca* (Del .) Parts on Antibiotic Resistant Bacterial Isolates. *European Journal of Medical Plants*, *4*(7), 854–864.

Uddin, M. B., Steinbauer, M. J., & Beierkuhnlein, C. (2011). Diversity, stand characteristics and spatial aggregation of tree species in a Bangladesh forest ecosystem. *Diversity*, *3*(3), 453–465. https://doi.org/10.3390/d3030453

Vayreda, J., Gracia, M., Martinez-Vilalta, J., & Retana, J. (2013). Patterns and drivers of regeneration of tree species in forests of peninsular Spain. *Journal of Biogeography*, *40*(7), 1252–1265. https://doi.org/10.1111/jbi.12105

Wang, S., Fan, J., Li, Y., & Huang, L. (2019). Effects of grazing exclusion on biomass growth and species diversity among various grassland types of the Tibetan Plateau. *Sustainability (Switzerland)*, *11*(6), 1-13. https://doi.org/10.3390/su11061705

Wang, X., Yan, J., Zhang, X., Zhang, S., & Chen, Y. (2020). *Organic manure input improves soil water and nutrients use for sustainable maize (Zea mays L.) productivity on the Loess Plateau*. ww.google.com

Wassie, H. M. (2011). *Potentials and Challenges of Alatish and Dinder National Parks (Ethiopia, Sudan) - Implementing Transboundary Park Cooperation*. University of Klagenfurt. www. google. com

Weber, J. C., & Montes, C. S. (2010). Correlations and clines in tree growth and wood density of *Balanites aegyptiaca* (L.) Delile provenances in Niger. *New Forests*, *39*(1), 39–49. https://doi.org/10.1007/s11056-009-9153-8

Weldemariam, C. E., Jakisa, S. E., & Ahebwe, A. D. (2017). Implication of forest zonation on tree species composition, diversity and structure in Mabira Forest, Uganda. *Environment, Earth and Ecology*, *1*(1), 112–122. https://doi.org/10.24051/eee/69224

Wich, S. A., Vogel, E. R., Larsen, M. D., Fredriksson, G., Leighton, M., Yeager, C. P., Brearley, F. Q., Schaik, C. P. Van, & Marshall, A. J. (2011). Forest fruit production is higher on Sumatra than on Borneo. *PLoS ONE*, *6*(6), 36–38. https://doi.org/10.1371/journal.pone.0021278

Williamson, K. (2017). Questionnaires, individual interviews and focus group interviews. *Research Methods: Information, Systems, and Contexts: Second Edition*. https:// doi. org/ 10. 1016/B978-0-08-102220-7.00016-9

Xu, S., Jagadamma, S., & Rowntree, J. (2018). Response of grazing land soil health to management strategies: A summary review. *Sustainability (Switzerland)*, *10*(12), 1–26.

https:// doi. org/ 10. 3390/su10124769

Yang, H., Zhang, P., Zhu, T., Li, Q., & Cao, J. (2019). The characteristics of soil C, N, and P stoichiometric ratios as affected by geological background in a karst graben area, Southwest China. *Forests*, *10*(7), 1–13. https://doi.org/10.3390/f10070601

Yirga, S. A. (2019). Agroforestry for sustainable agriculture and climate change: A review. *International Journal of Environmental Sciences & Natural Resources*, *19*(5), 127–137. https://doi.org/10.19080/ijesnr.2019.19.556022

Younis, A., Younis, I., Mustafa, H. F., & Ballal, M. A. (2018). Perception of the Local Community Towards Utilization and Role of Non-wood Forest Products in Bahr Alarab Locality , East. *IOSR Journal of Agriculture and Veterinary Science (IOSR-JAVS)*, *11*(6), 74–81. https:// doi. org/ 10.9790/2380-1106017481

Yousif, R. A. (2012). Abundance, Mayas preference and distribution of Birds in Dinder national park, Sudan. *World's Veterinary Journal*, *2*(3), 27–32.

Yousif, R. A., & Mohammed, F. A. (2012). Trends of poaching, Livestock Trespassing, Fishing and Resource Collection from 1986-2010 in Dinder National Park, Sudan. *Journal of Life Science and Biomedicine*, *2*(4), 105–109.

Zahawi, R. A., & Holl, K. D. (2009). Comparing the performance of tree stakes and seedlings to restore abandoned tropical pastures. *Restoration Ecology*, *17*(6), 854–864. https:// doi.org/ 10.1111/j. 1526-100X.2008.00423.x

Zamora, R., Gómez, J. M., Hódar, J. A., Castro, J., & García, D. (2001). Effect of browsing by ungulates on sapling growth of Scots pine in a mediterranean environment: Consequences for forest regeneration. *Forest Ecology and Management*, *144*(1–3), 33–42. https:// doi.org/ 10.1016/S0378-1127(00)00362-5

Zeng, Q., Liu, Y., Xiao, L., & Huang, Y. (2017). How fencing affects the soil quality and plant biomass in the grassland of the loess plateau. *International Journal of Environmental Research and Public Health*, *14*(10), 1-12. https://doi.org/10.3390/ijerph14101117

Zida, P. E., Neya, B. J., Soalla, R. W., Sereme, P., & Lund, O. S. (2018). Seed-priming of sorghum with antifungal extracts from *Balanites aegyptiaca* and Eclipta alba in different agro-ecological zones of Burkina Faso. *African Journal of Agricultural Research*, *13*(44), 2516–2525. https://doi.org/10.5897/ajar2018.13431

APPENDICES

Appendix 1: Questionnaire

Contribution of *Balanites aegyptiaca* to the forest-based livelihoods and households' income in and around Dinder Biosphere Reserve

1. **General information:**

Interview information:

Respondent No:------------- Date of interview:--------------- Time:--------------

Place information:

State:---------------------------- Locality:-------------------------------- District:-------------------------

Village:------------------------- Coordinates: ----------------------------

Gender: Male:-- ☐ Female: --☐

Social Status: Single:-- ☐ Married:-- ☐ No of family members:-- ☐

Age:

11 - 20	21 - 30	31 - 40	41 - 50	51 - 60	> 60

Years lived in the village:

< 5	6 - 10	11 - 15	16 - 20	21 - 25	> 25

Occupation:

Farmer	Pastoralist	Agro-pastoralist	Firewood producer	NTFP collector	Gov. worker	Other

Education:

Illiterate	Khalwa	Primary	Secondary	University	Post graduate

2. **Most utilized tree species in the reserve:** Please list the five top most utilized tree species for the following uses:

Food utilization:

1) ----------------- 2) ----------------- 3) ------------------ 4) ---------------- 5) --------------------

Medicinal purposes:

1) ----------------- 2) ----------------- 3) ------------------ 4) ---------------- 5) --------------------

Building materials:

1) ---------------- 2) ----------------- 3) ------------------ 4) ----------------- 5) --------------------

Fire wood and charcoal:

1) ---------------- 2) ----------------- 3) ------------------ 4) ----------------- 5) --------------------

Fodder for animals:

1) ---------------- 2) ----------------- 3) ------------------ 4) ----------------- 5) --------------------

3. **How far do you go to get these resources?**

< 1 km	1 - 3	4 - 6	7 - 9	12 - 15	> 15

4. **How often do you go (per month)?**

1	2	3	4	5	> 5

5. **Which material would you take, and how much?**

Materials	Fruits		Bark		Leaves		Wood		Roots	
Quantity	< 3 kg		< 3 kg		< 3 kg		< $1m^3$		< 3 kg	
	3–5 kg		3–5 kg		3–5 kg		1-3 m^3		3–5 kg	

	6-8 kg		6-8 kg		6-8 kg		4-6 m^3		6-8 kg	
	9-11kg		9-11kg		9-11kg		7-9 m^3		9-11 kg	
	12-14kg		12-14kg		12-14kg		10-12m^3		12-14kg	
	≥ 15 kg		≥ 15 kg		≥ 15 kg		≥ 7 m^3		≥ 8 kg	

6. Please, if *Balanites aegyptiaca* is among the most utilized tree species, list the five common uses of its fruits:

1) --
2) --
3) --
4) --
5) --

7. Please, if *Balanites aegyptiaca* is among the most utilized tree species, list the five common uses of its leaves:

1) --
2) --
3) --
4) --
5) --

8. Please, if *Balanites aegyptiaca* is among the most utilized tree species, list the five common uses of its bark:

1) --
2) --
3) --
4) --
5) --

9. Please, if *Balanites aegyptiaca* is among the most utilized tree species, list the five common uses of its wood:

1) --
2) --

3) ---
4) ---
5) ---

10. Please, if *Balanites aegyptiaca* is among the most utilized tree species, list the five common uses of its roots:

1) ---
2) ---
3) ---
4) ---
5) ---

11. Among the family members, who is responsible for collecting and selling these product (s)?

Father	Mother	Kids	All

12. Experience, selling markets, collected quantities and the revenue history for people working with and consuming *Balanites aegyptiaca*:

How many years you have in selling *B. aegyptiaca* products?

< 1 year	1 – 3 year	4 – 6 years	7 – 9 years	12 – 15 years	> 15 years

How many years you have in using *B. aegyptiaca* products?

< 1 year	1 – 3 year	4 – 6 years	7 – 9 years	12 – 15 years	> 15 years

If you are collecting these products for income generation, at which market you usually sell your products?

Village	Locality	District	Town

Please, estimate the quantity that you collected last year (in bags): -----------------------------------

Please, estimate the income that you generated last year (SDG): -------------------------------------

Please, estimate the income that you generated during the previous season (SDG): ----------------

Please, seasons): ---

13. Information regarding the collected *Balanites aegyptiaca* products:

Has your collected amount been stable over the last years? Yes:-- ☐ No: --☐, if No:

Declining:-- ☐ Increasing: --☐

Has there been a very good year for *B. aegyptiaca* products? If so, which one? ---------------

What is the trend of *B aegyptiaca*? Decreasing:-- ☐ Stable: --☐ Increasing:-- ☐

How many fruits do you usually collect per tree? ---

Are you plugging them or just collect from the soil? ---

Are you picking and collecting fruits from and under tall / old trees? Yes:-- ☐ No: --☐

If No: Young trees:-- ☐ Mature trees: --☐ Over mature:-- ☐ All types: --☐

How long it takes until these fruits sprout? ---

Are you keeping some back some fruits for planting? Yes:-- ☐ No: --☐

If yes, how much? ---

Sprouts of young *B. aegyptiaca* trees are: In batches:-☐ Infrequent: ☐ Across the year: ☐

You think why? ---

14. List the reasons behind the degradation of *Balanites aegyptiaca* stock in the reserve:

a) -- b) ---
c) -- d) ---
e) -- f) ---
g) -- h) --

15. State the alternative species that can be used at absence of *Balanites aegyptiaca*:

a) -- b) ---
c) -- d) ---
e) -- f) ---

16. Rare and disappeared tree species in the area:

a) Rare tree species:
1) ---------------- 2) ----------------- 3) ----------------- 4) --------------- 5) -----------------
b) Disappeared tree species:
1) --------------- 2) ------------------ 3) ----------------- 4) ---------------- 5) -----------------

17. The most dominant livestock grazing/browsing species in the area:

a) --------------------------- b) ---------------------------------- c) -------------------------------

18. Information regarding livestock and their browsing activities:

How frequently do you see livestock eating *B. aegyptiaca*? ---

Which is the main browsing species? ---

Do your cattle eat *B. aegyptiaca*? Old trees ? seedlings ? saplings? -----------------------------------

Does livestock eat fruits? Bark? --

Any particular season when *B. aegyptiaca* is preferred by livestock? ---------------------------------

Have livestock numbers increased in the area? --

How many livestock does you have and of which species? ---

19. Status of wild animal in the area:

Frequently observed animal/(s) in the past (last 5 years):

1) ---------------- 2) ----------------- 3) ---------------- 4) ---------------- 5) -----------------

Frequent observed animal/(s) now (current year):

1) ----------------- 2) ------------------ 3) ----------------- 4) ----------------- 5) -------------------

20. Have you seen wild animals feeding on *B. aegyptiaca*? Yes: -----☐ No :------ ☐

21. If yes, how many times? And where? --

22. Climate change issue:

Rainfall (Last 10 years): Increased:----- ☐ Decreased: -----☐ Constant :------ ☐

Flooding (Last 10 years): Increased:----- ☐ Decreased: -----☐ Constant :------ ☐

Soil erosion (Last 10 years): Increased:----- ☐ Decreased: -----☐ Constant :------ ☐

23. Do you think *B. aegyptiaca* helps improving the soil? If so, how? …

24. Your advice to improve the current status of the reserve: you mean the transition zone of the reserve?

Thank you so much for your assistance and support

RESEARCH OUTPUTS

(i) Published Research Articles

Mohammed, E. M. I., Elhag, H. A. M., Ndakidemi, P. A., Treydte, A. C. (2021). Anthropogenic Pressure on Tree Species Diversity, Composition, and Growth of *Balanites aegyptiaca* in Dinder Biosphere Reserve, Sudan. *Plants*, 10, 1-18. https:// doi. org/ 10.3390/ plants10030483

Mohammed, E. M. I., Elhag, H. A. M, Minnick, T. J., Ndakidemi, P. A., Treydte, A. C. (2021). Livestock Browsing Threatens the Survival of *Balanites aegyptiaca* Seedlings and Saplings in Dinder Biosphere Reserve, Sudan. *Journal of Sustainable Forestry*, 2021, 1-9, DOI: 10.1080/10549811.2021.1935279

Mohammed, E. M. I., Elhag, H. A. M., Ndakidemi, P. A., Treydte, A. C. (2021). Illegal harvesting threatens fruit production and seedling recruitment of *Balanites aegyptiaca* in Dinder Biosphere Reserve, Sudan. *Global Ecology and Conservation*, 29 (2021), 1-9.

(ii) Poster Presentation