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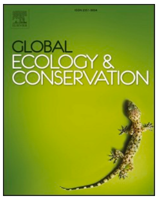

# Illegal harvesting threatens fruit production and seedling recruitment of *Balanites aegyptiaca* in Dinder Biosphere Reserve, Sudan

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ABSTRACT

Illegal harvesting negatively affects the forest tree populations, particularly in sub-Saharan Africa, but little is known how fruit production and seedling recruitment are impacted. We assessed recruitment parameters of *Balanites aegyptiaca* trees in the Dinder Biosphere Reserve (DBR) across 100 sample plots of 25 m x 40 m in both human-impacted (disturbed) and undisturbed sites. We found that the average number of fruiting branches of *B. aegyptiaca* in the undisturbed sites were three times as high as those in the disturbed sites ($F_{1,98} = 139$, $P < 0.001$). Further, fruiting branches were positively correlated with crown width ($R^2 = 0.71$, $\beta = 7.1$, $P = 0.01$) across both sites. The height and crown width of *B. aegyptiaca* in the undisturbed sites were double that of the disturbed sites ($F_{1,196} = 80$, $P < 0.001$; $F_{1,196} = 94.8$, $P < 0.001$). Saplings and seedlings at the undisturbed sites were three times and twice that of the disturbed sites, respectively ($F_{1,196} = 94.5$, $P < 0.001$; $F_{1,196} = 100.8$, $P < 0.001$), with a positive correlation to the average number of fruiting branches ($R^2 = 0.74$, $\beta = 0.45$, $P < 0.001$). The soil nitrogen and phosphorus contents beneath trees in the undisturbed sites were almost double that of those in the disturbed sites ($F_{1,196} = 68.1$, $P < 0.001$; $F_{1,196} = 97.9$, $P < 0.001$) while sodium and electrical conductivity were by about 50% lower ($F_{1,196} = 535.8$, $P < 0.001$; $F_{1,196} = 16.1$, $P < 0.001$). We conclude that illegal harvesting in DBR severely reduced tree structure and recruitment parameters of *B. aegyptiaca*, which might also have impacted soil fertility. We urge for intensive monitoring and awareness-raising programs to conserve this vulnerable tree species.

## 1. Introduction

The worldwide rapid growth of human populations implies a high demands for natural resources which reduces the biodiversity of fauna and flora (Cantarello et al., 2014; Fakhry et al., 2020; Mohammed et al., 2021). Particularly in sub-Saharan countries, illegal

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harvesting is common and has led to various ecological problems such as habitat fragmentation, removal of seed-producing trees, deforestation, and land degradation (Adekunle and Olagoke, 2011; Gebeyehu et al., 2019; Hasoba et al., 2020; Piabuo et al., 2021). Moreover, removal of the tree crown branches for livestock feeding, debarking of its stem for medicinal purposes, and logging of the entire tree are harmful to mature and juvenile trees (Assogbadjo et al., 2010; Piabuo et al., 2021; Sukhbaatar et al., 2019). To conserve and manage the forest resources, knowledge of the tree population structure, species composition and developmental stages is essential (Mohammed et al., 2021; Singh et al., 2016).

Forest inventories can help understand the plant species composition and structure and to assess how forest populations have been affected by biotic factors such as illegal harvesting (Dau et al., 2015; Heym et al., 2021; Simons et al., 2021; Storch et al., 2018). Moreover, the assessment of tree biodiversity, natural regeneration, growing stock, and ecosystem services, as well as the dendrometric parameters and species proliferation, can be achieved through modern forest inventory (Asbeck et al., 2021; Heym et al., 2021; John et al., 2020; Mohammed et al., 2021; Simons et al., 2021). Crown width, tree height, and diameter at breast height are among the key dendrometric parameters that can indicate tree population status (Ibrahim et al., 2015; Ibrahim and Osman, 2014; Mohammed et al., 2021). Tall trees with a large diameter and crown width are usually more subjected to illegal felling than smaller ones (Ibrahim and

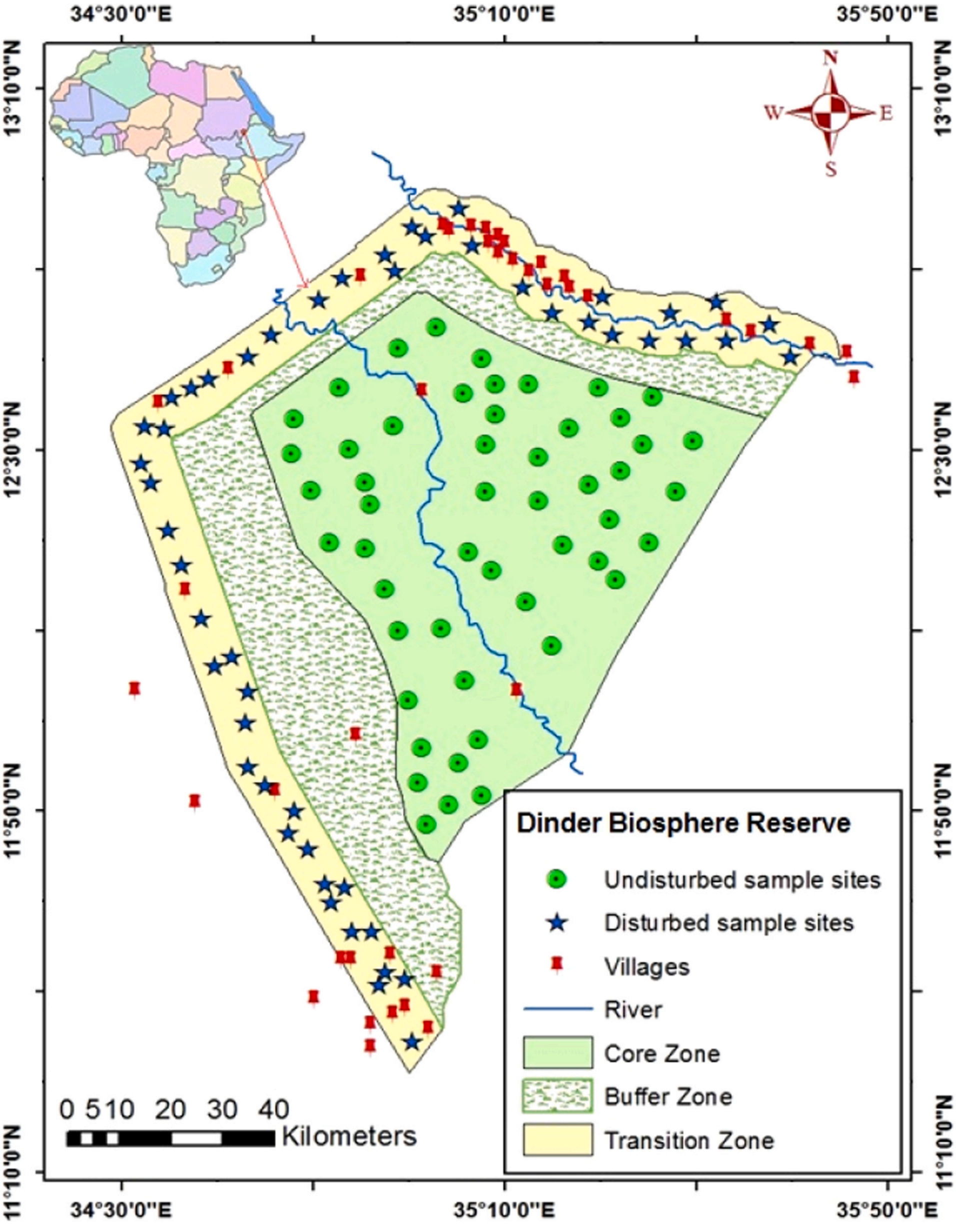

**Fig. 1.** Map of Dinder Biosphere Reserve (DBR) and the disturbed and undisturbed sampling sites, at which we measured dendrometric parameters of *Balanites aegyptiaca* and other tree species over a period of one year, from February 2020 to February 2021.

Osman, 2014; Mohammed et al., 2021; Ouédraogo et al., 2019; Ranaivoson et al., 2015). Hence, we would expect a severely damaged population to comprise few adult and fruit-producing trees but rather a less productive tree population of smaller trees.

Dinder Biosphere Reserve (DBR) is the oldest biosphere reserve in Sudan and hosts more than 35 tree species (Elmekki, 2008; Hassaballah et al., 2020; Mahgoub, 2014; Mohammed et al., 2021). These species are varying from gum producing trees such as *Acacia polyacantha, Acacia senegal, Acacia seyal,* and *Boswellia papyrifera*, to trees with edible fruits and medicinal potentials such as *Anogeissus leiocarpus, Balanites aegyptiaca, Combretum hartmannianum, Grewia mollis, Hyphaena thebiaca, Tamarindus indica,* and *Ziziphus spina-christi* (Hassaballah et al., 2016; Mohammed et al., 2021; Wassie, 2011). Among these tree species, *Balanites aegyptiaca* is of high significance as it has been traditionally used in Sudan for centuries for food, feed, medicine, and timber (Adam et al., 2013; Elbadawi et al., 2017; Elfeel et al., 2007; Hasoba et al., 2020; Hassanin et al., 2018). However, little is known about how this traditional use has been affecting the population and its proliferation, as well as the soil chemical properties.

Our study aimed at exploring the effects of illegal harvesting of *Balanites aegyptiaca* trees and their parts on their capability of fruit

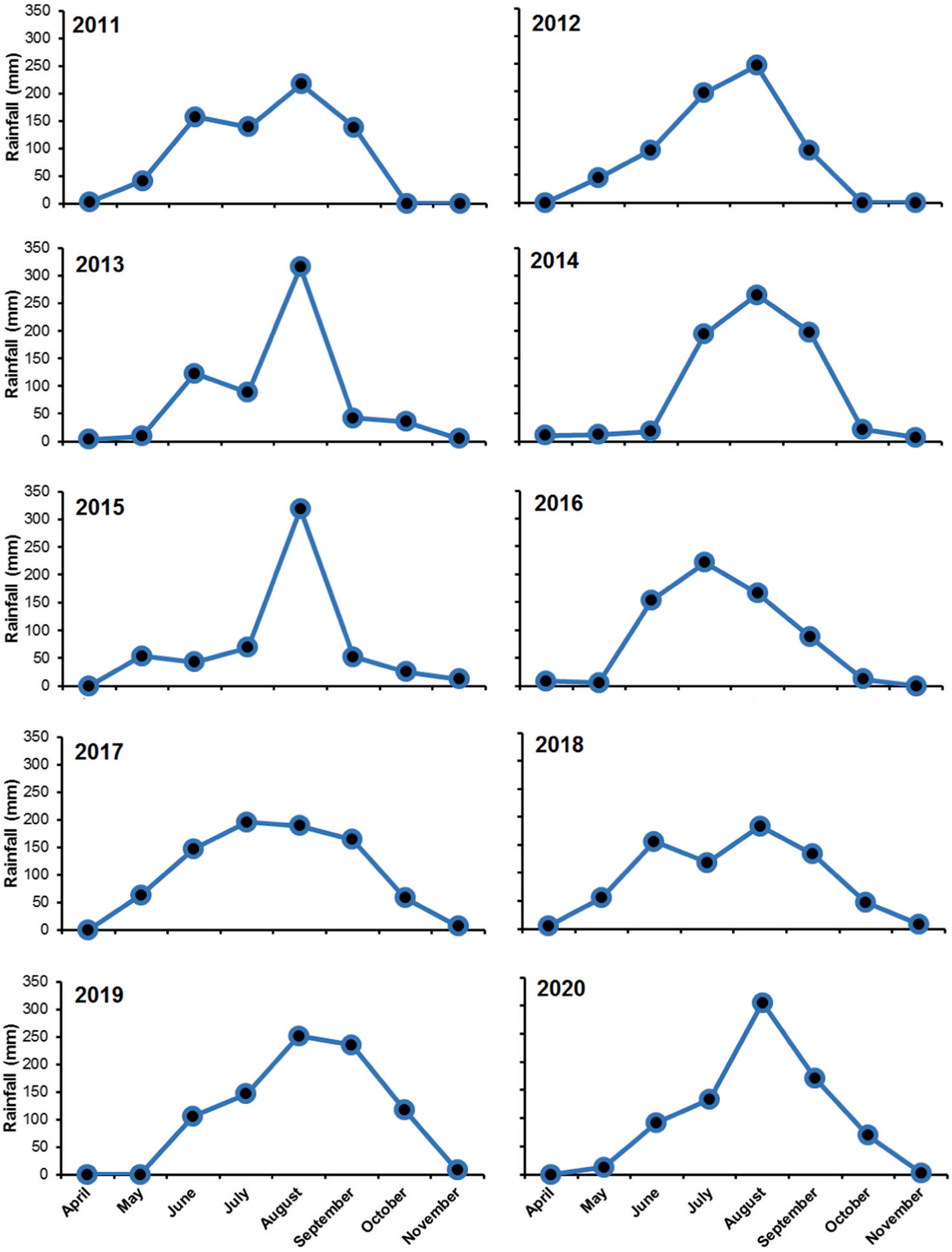

**Fig. 2.** Average monthly rainfall for disturbed and undisturbed sites in DBR for ten years (2011–2020), calculated based on the data obtained from Sudan Meteorological Authority (SMA).

production and seedling recruitment in DBR. Moreover, as mature trees can improve the soil quality (Ghosh and Devi, 2019; Omar and Muhammad, 2016; Treydte et al., 2007), and the reduction of tree crown size can interrupt this process (Kutnar et al., 2019; Ouédraogo et al., 2019; Sukhbaatar et al., 2019), we also compared soil chemical properties beneath tall trees in disturbed and undisturbed areas of DBR.

We hypothesized that trees in undisturbed sites will have higher crown width, tree height, diameter at breast height, and average number of fruiting branches compared to those at the disturbed sites. Moreover, as *B. aegyptiaca* is highly utilized by the local community within and around the reserve (Adam et al., 2013; Hasoba et al., 2020; Mohammed et al., 2021), we expected that this species will be more affected than the other tree species.

Further, we hypothesized that the disturbed sites of DBR will have lower seedling and sapling numbers of *B. aegyptiaca* and other

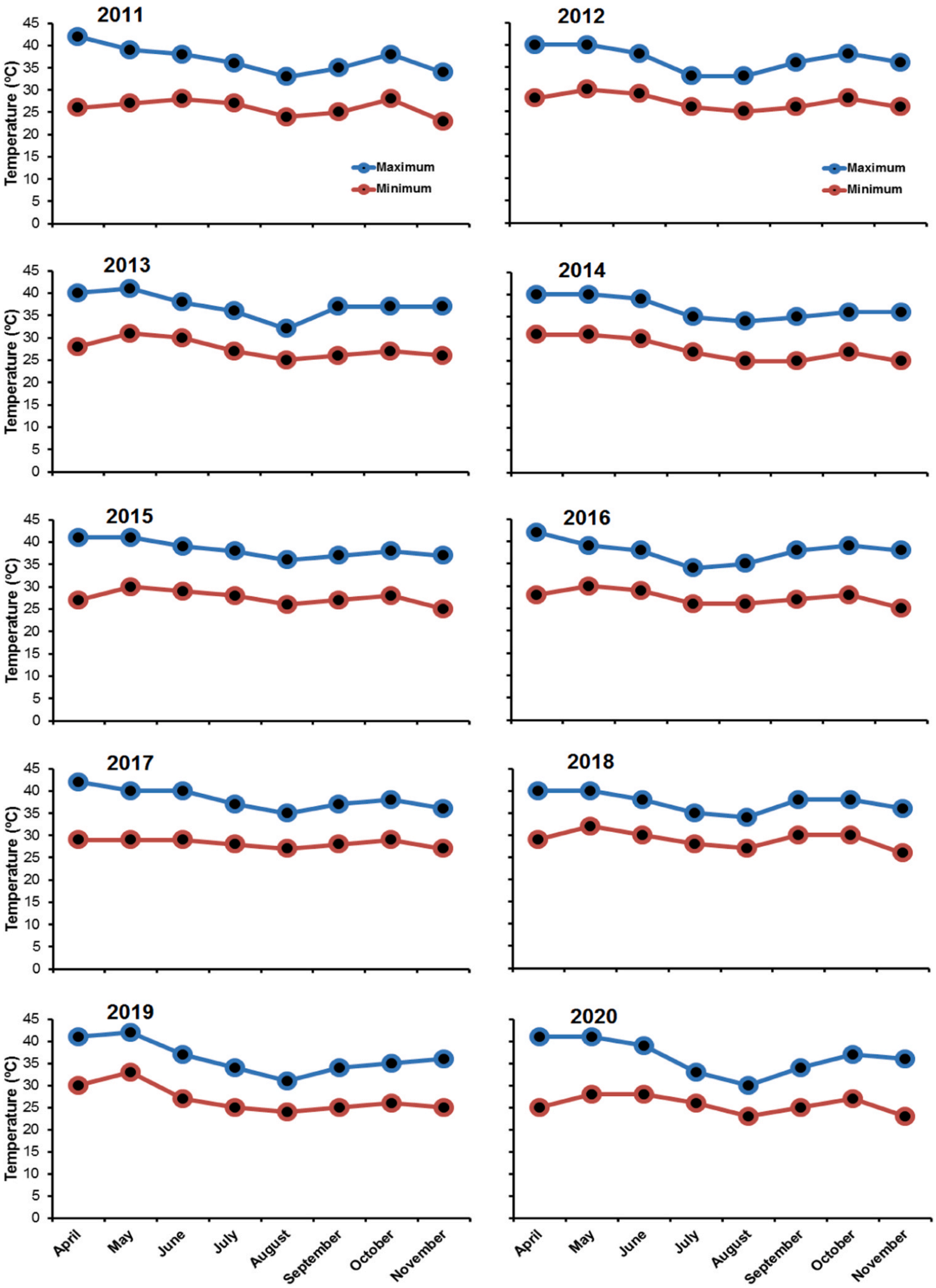

**Fig. 3.** Average monthly maximum and minimum temperature for disturbed and undisturbed sites in DBR for ten years (2011–2020), calculated based the data obtained from SMA.

tree species than undisturbed sites. We also predict that the soil chemical properties will be different between the disturbed and undisturbed sites, with lower contents beneath *B. aegyptiaca* compared to other tree species such as Acacia species, which are nitrogen-fixers.

Our study will help the conservation and the sustainable management of this vulnerable tree species by the provision of up-to-date information about its population structure and the effect of disturbance on its sensitive developmental stage in Sudan. Moreover, the study findings can be useful for the conservation of similar ecosystems at regional and global levels where humans harvest forest resources at different intensities.

## 2. Materials and methods

### *2.1. Study area*

The Dinder Biosphere Reserve (DBR) is positioned at 12°- 26N, 12°- 42´N, 34°- 48E and 35°- 02E (Fig. 1) with a total area of 10,291 km$^2$ (Mahgoub, 2014). We characterized the rainfall and temperature in the disturbed and non-disturbed sites for ten years (2011–2020) based on the data of the Sudan Meteorological Authority ( Figs. 2 and 3). The average monthly rainfall varied from < 5 mm in April and November to > 250 mm in August (Fig. 2), while the average monthly minimum and maximum temperature vary between 24 °C in August and November to 29 °C in May and 33 °C in August to 41 °C in April (Fig. 3), respectively.

The DBR comprises three zones of different protection status (Elmekki, 2008): the transition zone as an outer zone of the reserve is subjected to high illegal harvesting and livestock grazing originating from various villages and human settlements (Hassaballah et al., 2020; Mohammed and Hashim, 2015). The buffer and core zones are exposed to lower and no human disturbances, respectively (Mahgoub, 2014; Yousif and Mohammed, 2012). We sampled the transition zone as our “disturbed site” and the core zone as “undisturbed site” (Fig. 1, Plates 1 and 2). The common tree species in the study area were, *Balanites aegyptiaca, Combretum hartmannianum, Acacia seyal, Anogeissus leiocarpus, Lannea fruticosa, Tamarindus indica, Terminalia brownii* and *Ziziphus spina-christi* (Hassaballah, 2020; Mahgoub, 2014; Mohammed et al., 2021).

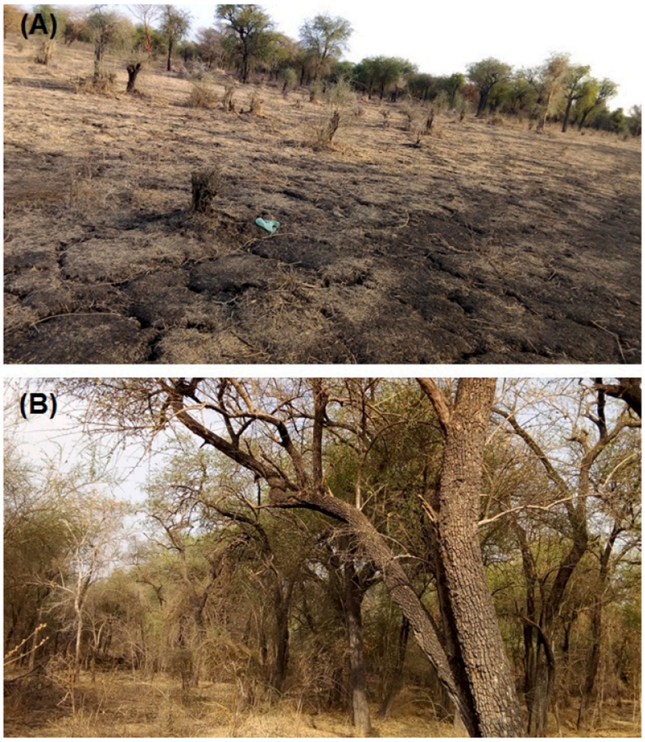

**Plate 1.** Illustrates parts of the disturbed and undisturbed sites of the Dinder Biosphere Reserve where this study has been conducted in the period from February 2020 to February 2021. (A) Disturbed sites, and (B) Undisturbed sites.

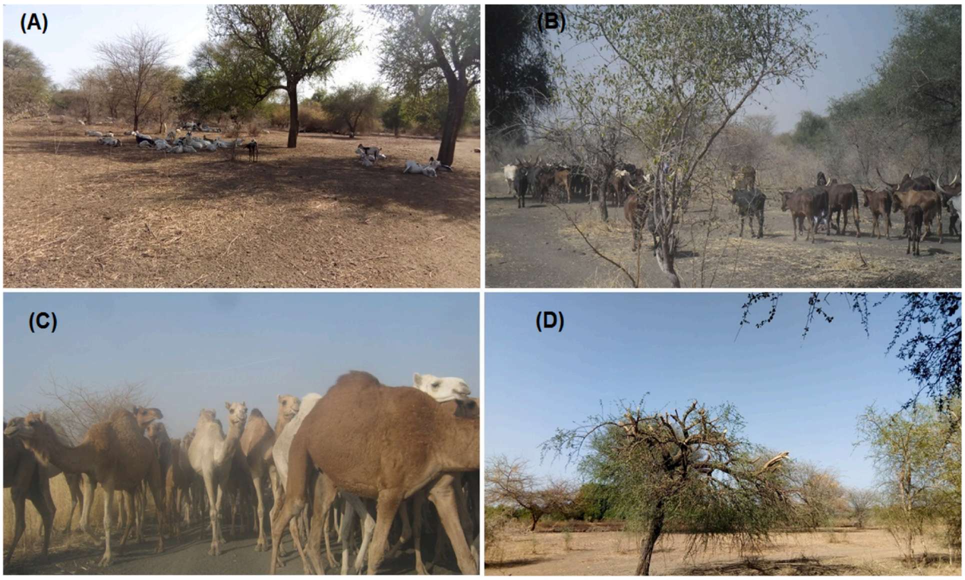

**Plate 2.** Displays; (A) sheep and goats, (B) cattle, (C) camels, and (D) illegal cutting of crown branches for livestock feeding that have been observed and assessed in the disturbed sites of the Dinder Biosphere Reserve over one year from February 2020 to February 2021.

## *2.2. Data collection*

### *2.2.1. Tree species composition and forest inventory data*

The forest inventory process was accomplished 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. At each sample plot, all tree species were identified and the diameter at breast height (DBH), total tree height (TH), and crown width (CW) were measured for mature trees (> 7 cm in DBH) (Ibrahim et al., 2018; Osman and Idris, 2012). Caliper, Suunto clinometer, and tape were used for measuring DBH, TH, and CW, respectively (Ibrahim and 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, we 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 and Kushwaha, 2006; Wich et al., 2011). Also, we counted and recorded the number of seedlings and saplings for each sample plot, where we defined seedlings as being < 3 cm in diameter, and sapling diameters in ranges < 7 cm and > 3 cm see also (Papadopoulos et al., 2017; Tripathi and Tripathi, 2010).

### *2.2.2. Soil sampling procedure and chemical analysis*

In each of the one hundred inventory sample plots, we 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. We performed all soil analyses 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). We also used Inductively coupled plasma optical emission spectrometry (ICP-OES) with nitric and perchloric acid to measure the concentrations of P, Na, and K (Hofhansl et al., 2020; Scholten et al., 2017). Moreover, for measuring the soil pH we used 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). We calculated the C:N ratio as an atomic ratio using organic carbon to nitrogen (Yang et al., 2019).

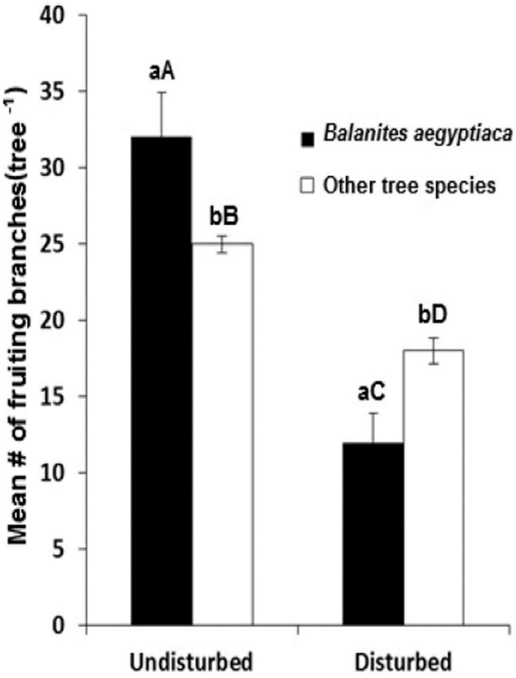

**Fig. 4.** Average (± SE) number of fruiting branches of *Balanites aegyptiaca* and other tree species sampled in the disturbed and undisturbed sites of the Dinder Biosphere Reserve, February 2020 to February 2021. Various letters above bars show significant differences between different species, i.e., *B. aegyptiaca* vs other tree species (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc tests with $P < 0.05$.

### 2.3. Data analysis

We tested for normality and homogeneity using Shapiro Wilk and Kolmogorov-Smirnov D tests (Missanjo et al., 2015; Truong and Marschner, 2018). We used two-way ANOVA to analyze the data of DBH, TH, CW, FB, and soil variables within and between the disturbed and undisturbed sites across the study area (Ghosh and Devi, 2019; Hasnain et al., 2020). To explore the association between the tree crown width and the number of seedlings and saplings under trees, we 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 and soil chemical properties (N, SOC, K, P, Na, and C/N). To distinguish the significant differences between different measured variables in the studied sites, we used Tukey's tests at $\alpha = 0.05$ (Ghosh and Devi, 2019; Truong and Marschner, 2018). All statistical analyses were performed using JAMOVI (version 1.1.7) and Minitab (version 17).

## 3. Results

### 3.1. Crown width, height, and fruiting branches

The average number of fruiting branches of *B. aegyptiaca* and other tree species were three and two times higher in the undisturbed sites than that in the disturbed sites, 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. 4). The number of *B. aegyptiaca* fruiting branches was by about 30% higher in undisturbed sites but significantly lower in disturbed sites compared to the other tree species (Fig. 4). The correlation between the fruiting branches and crown width of *B. aegyptiaca* and other tree species in both sites illustrated strong positive relationships ($\beta = 7.1$, $P = 0.01$; $\beta = 8.2$, $P = 0.02$, respectively, Fig. 5).

The undisturbed sites 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. 6). The values of H and CW of *B. aegyptiaca* in the undisturbed sites were double that of the disturbed sites ($t = 52.3$, $P < 0.001$; $t = 37.4$, $P = 0.001$, Fig. 6).

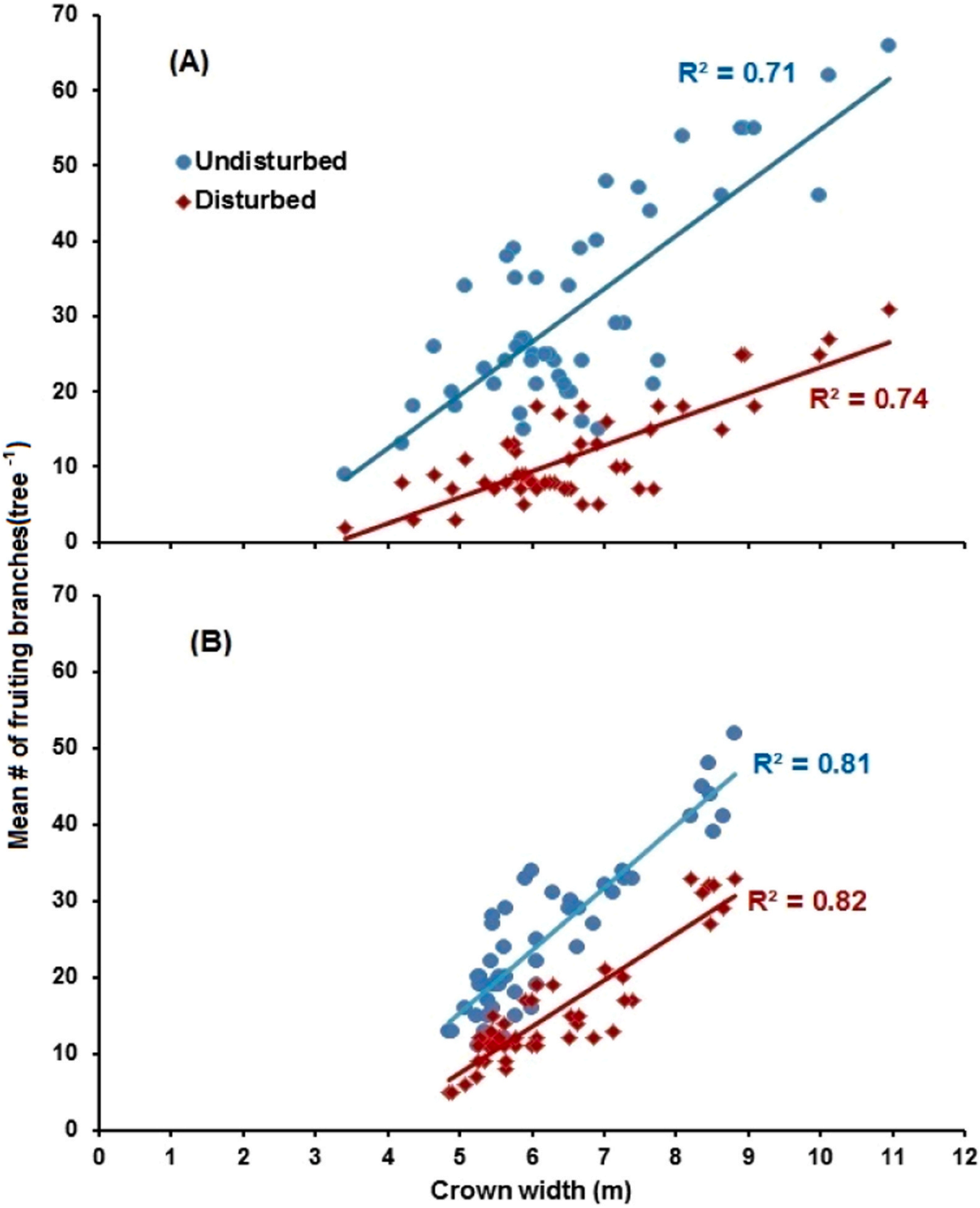

**Fig. 5.** Correlation between crown width and fruiting branches for (A) *Balanites aegyptiaca* and (B) other tree species in the undisturbed and disturbed sites at Dinder Biosphere Reserve, measured February 2020 to February 2021.

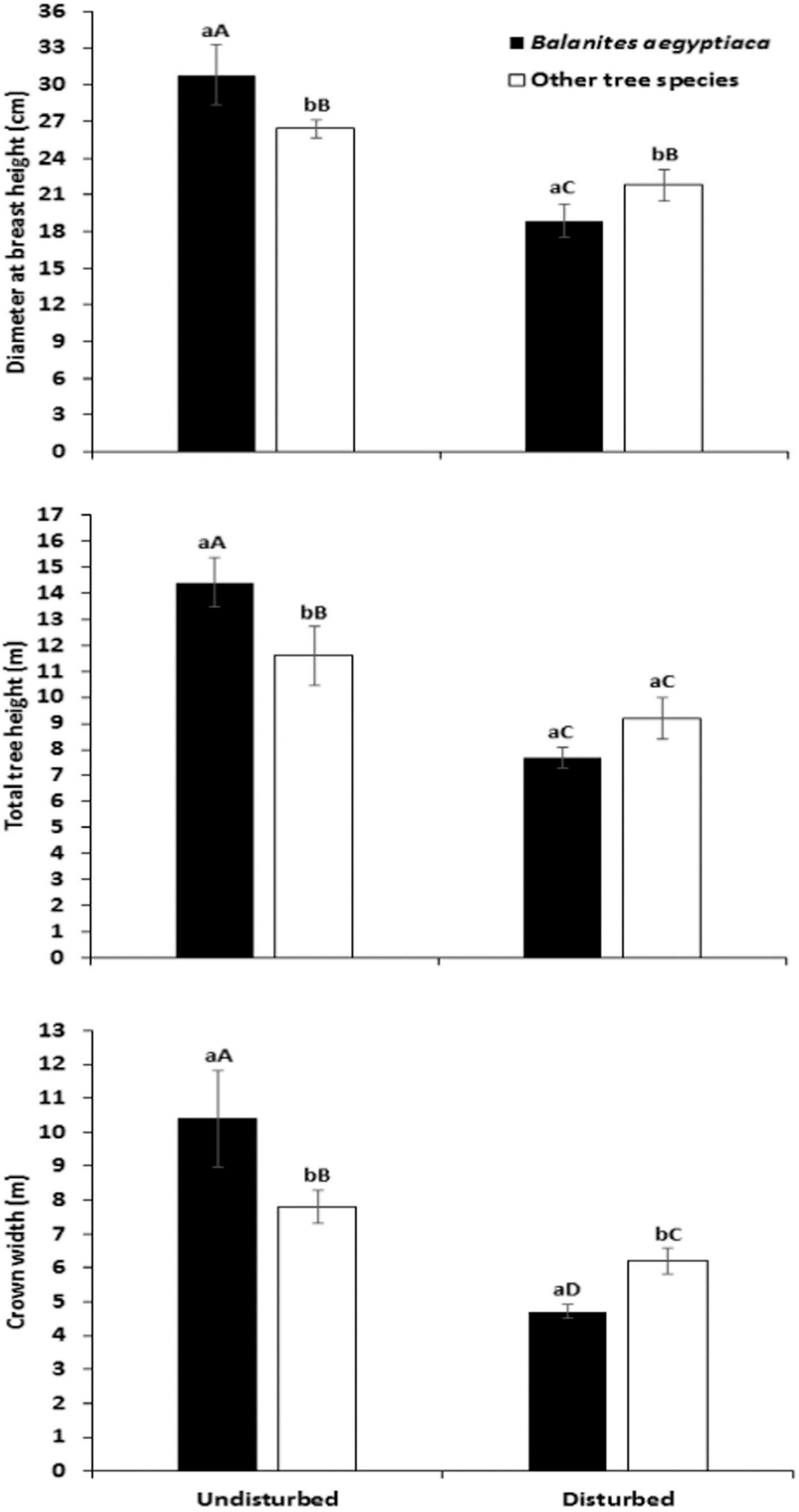

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**Fig. 6.** Average (± SE) tree diameter at breast height, tree height, and crown width of *B. aegyptiaca* and other tree species in the undisturbed and disturbed sites of the Dinder Biosphere Reserve measured February 2020 to February 2021. Various letters above bars signpost significant differences between different species, i.e., *B. aegyptiaca* vs other tree species (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc tests ($P < 0.05$) for the three measured parameters.

### *3.2. Seedling, sapling, and tree density*

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 undisturbed sites being three times and double that of the disturbed sites ($F_{1,196} = 94.5$, $P < 0.001$; $F_{1,196} = 23.7$, $P < 0.001$, respectively). Other tree species saplings were twice as many in the undisturbed as in the disturbed sites ($F_{1,196} = 63.7$, $P = 0.001$, Fig. 7). Seedlings showed similar significant differences between sites ($F_{1,196} = 100.8$, $P < 0.001$, Fig. 7).

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 undisturbed and disturbed sites, respectively (Fig. 8). 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 undisturbed and disturbed sites, respectively (Fig. 8).

### *3.3. The chemical properties of soil beneath the affected and healthy trees*

The N and P beneath tree canopies in the undisturbed sites were almost double that of the disturbed sites, 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. 9, 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. 9, B and F).

The disturbed sites showed twice as high Na and ECe compared to the undisturbed sites ($F_{1, 196} = 535.8$, $P < 0.001$; $F_{1, 196} = 16.1$, $P < 0.001$, respectively, Fig. 9, D and H), while K showed no significant differences within the sites between *B. aegyptiaca* trees and other tree species, was significant between sites ($F_{1, 196} = 5.4$, $P = 0.464$; $F_{1, 196} = 43.5$, $P < 0.001$, respectively, Fig. 9, C). Soil pH displayed the same pattern ($F_{1, 196} = 59.3$ and $P = 0.041$, Fig. 9, G).

Furthermore, there was a strongly positive correlation between the N, SOC, K, P, and the crown width of adult *B. aegyptiaca* trees ($\beta = 0.09$, $P < 0.001$; $\beta = 0.11$, $P < 0.001$; $\beta = 0.09$, $P < 0.001$; $\beta = 0.91$, $P < 0.001$, respectively), while for Na and the C/N ratio was negative ($\beta = - 0.64$, $P = 0.011$; $\beta = - 2.66$, $P = 0.001$, respectively), (Fig. 10).

## 4. Discussion

### *4.1. Crown width, height, and fruiting branches*

Our study findings of smaller tree crown width and height in the disturbed sites in line with (Abdou et al., 2016), (Assogbadjo et al., 2010), (Mohammed et al., 2021), and (Neelo et al., 2015), who 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. 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. We 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, our 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 our disturbed sites in the Dinder Biosphere Reserve can be attributed to the overutilization and illegal harvesting activities by the local community in and around the reserve. Therefore, we 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.

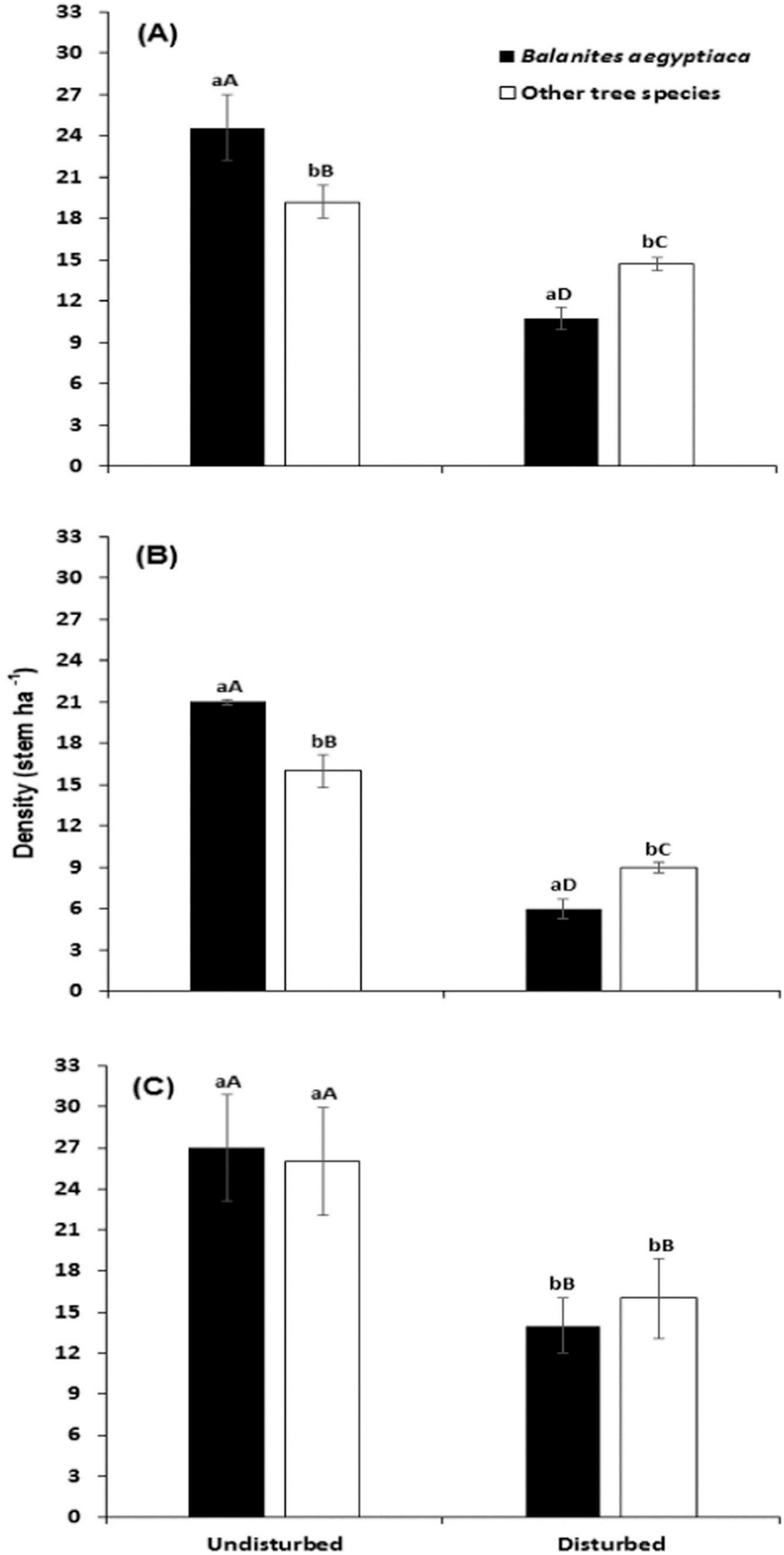

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**Fig. 7.** Average (± SE) density of *B. aegyptiaca* and other tree species in the undisturbed and disturbed sites of the Dinder Biosphere Reserve measured February 2020 to February 2021. (A) = Mature trees, (B) = Saplings, and (C) = Seedlings. Various letters above bars signpost significant differences between different species, i.e., *B. aegyptiaca* vs other tree species (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc tests ($P < 0.05$).

### *4.2. Seedling, sapling, and tree density*

Our 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 (Ball and Tzanopoulos, 2020; Chaturvedi et al., 2012; Ibrahim and Hassan, 2015; Osman and Idris, 2012), who 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. 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 and 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. Moreover, (Gaisberger et al., 2020) concluded that overgrazing and overexploitation were the main threats to the population of Juglans regia in Kyrgyzstan, Tajikistan, and Uzbekistan.

As hypothesized, our 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 Oué-draogo 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, as well as overgrazing by livestock. During our fieldwork activities we observed 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*. Moreover, the lower annual rainfall in 2013, 2015, and 2016 might be the main contributor of low recruited saplings at both disturbed and undisturbed sites.

### *4.3. The chemical properties of soil beneath the affected and healthy trees*

Soil nitrogen, organic carbon, potassium, and phosphorus were all higher beneath trees growing in our undisturbed sites compared to the disturbed sites. However, generally, within the sites, 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 and Muhammad, 2016; Raddad et al., 2006). Our 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 and Olagoke, 2011; Jurgensen et al., 1997; Martinelli et al., 2000; Missanjo and 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 has widely been used in Sudan for food, feed, and medicinal purposes (Adam et al., 2013; Fadl, 2015; Mohammed et al., 2021), we 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.

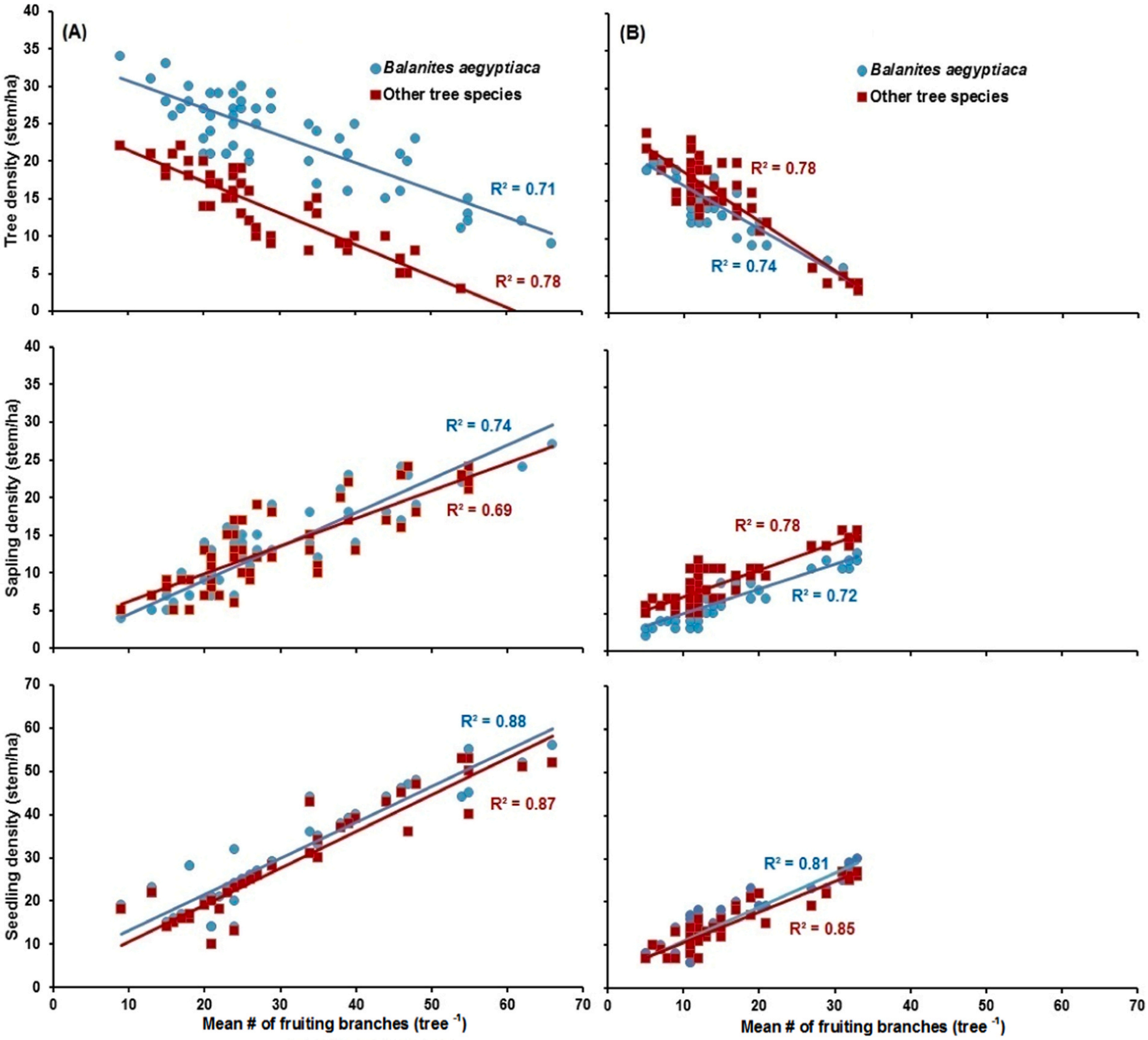

**Fig. 8.** Correlation between the density of adult trees, saplings, and seedlings, and fruiting branches for *B. aegyptiaca* and other tree species in (A) the undisturbed and (B) disturbed sites at Dinder Biosphere Reserve, measured February 2020 to February 2021.

## 5. Conclusion

We conclude that tall trees with large crown widths produce the largest number of fruiting branches and, thus, contribute strongly to both soil nutrient contents as well as tree species proliferation and resilience in the Dinder Biosphere Reserve. We found that *Balanites aegyptiaca* was severely influenced by illegal harvesting, and their population dynamics were strongly interrupted. Therefore, to increase its natural regeneration and the recruitment of new seedlings and saplings, it is important to eliminate all forms of illegal harvesting with particular consideration to tree pollarding (debranching of the tree crown). We further see a degradation of soil fertility in DBR, which will consequently affect fruit production and seedling recruitment in the reserve. We further found that the natural regeneration of other tree species besides *B. aegyptiaca* was also disturbed due to their poor recruitment in Dinder Biosphere Reserve. We also recently reported that anthropogenic pressure affected the natural regeneration of more than 85% of the tree species found in the transitional zone of the Dinder Biosphere Reserve, highlighting the urgency of protective measures (Mohammed et al., 2021). We propose that livestock 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. Secondly, stem debarking, uprooting, leaf defoliation, pollarding, and illegal logging, should be prohibited and regulated through strict policies. However, the introduction of community forestry and environmental-friendly activities such as honey beekeeping, can satisfy the needs of the local community, and reduces their pressure on the biosphere reserve, as well as the recovery of degraded sites.

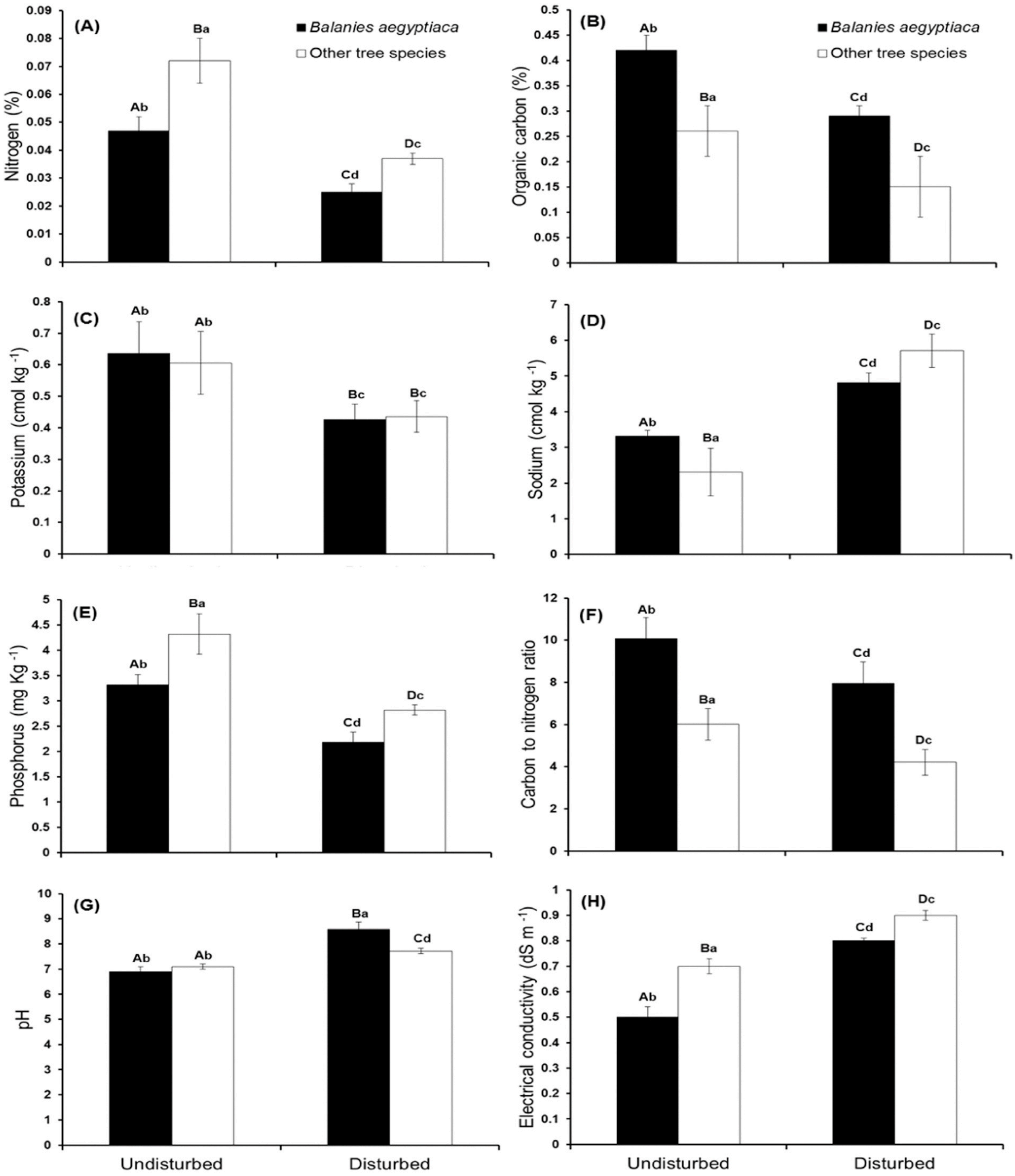

**Fig. 9.** Average (± SE) (A) nitrogen, (B) organic carbon, (C) potassium, (D) sodium, (E) phosphorus, (F) carbon to nitrogen ratio, (G) pH, and (H) electrical conductivity of *B. aegyptiaca* and other tree species in the undisturbed and disturbed sites of Dinder Biosphere Reserve measured in February 2020 to February 2021. Various letters above bars signpost significant differences between different species, i.e., *B. aegyptiaca* vs other tree species (small letters) and between the sites (capital letters) according to Tukey's Post-Hoc tests ($P < 0.05$).

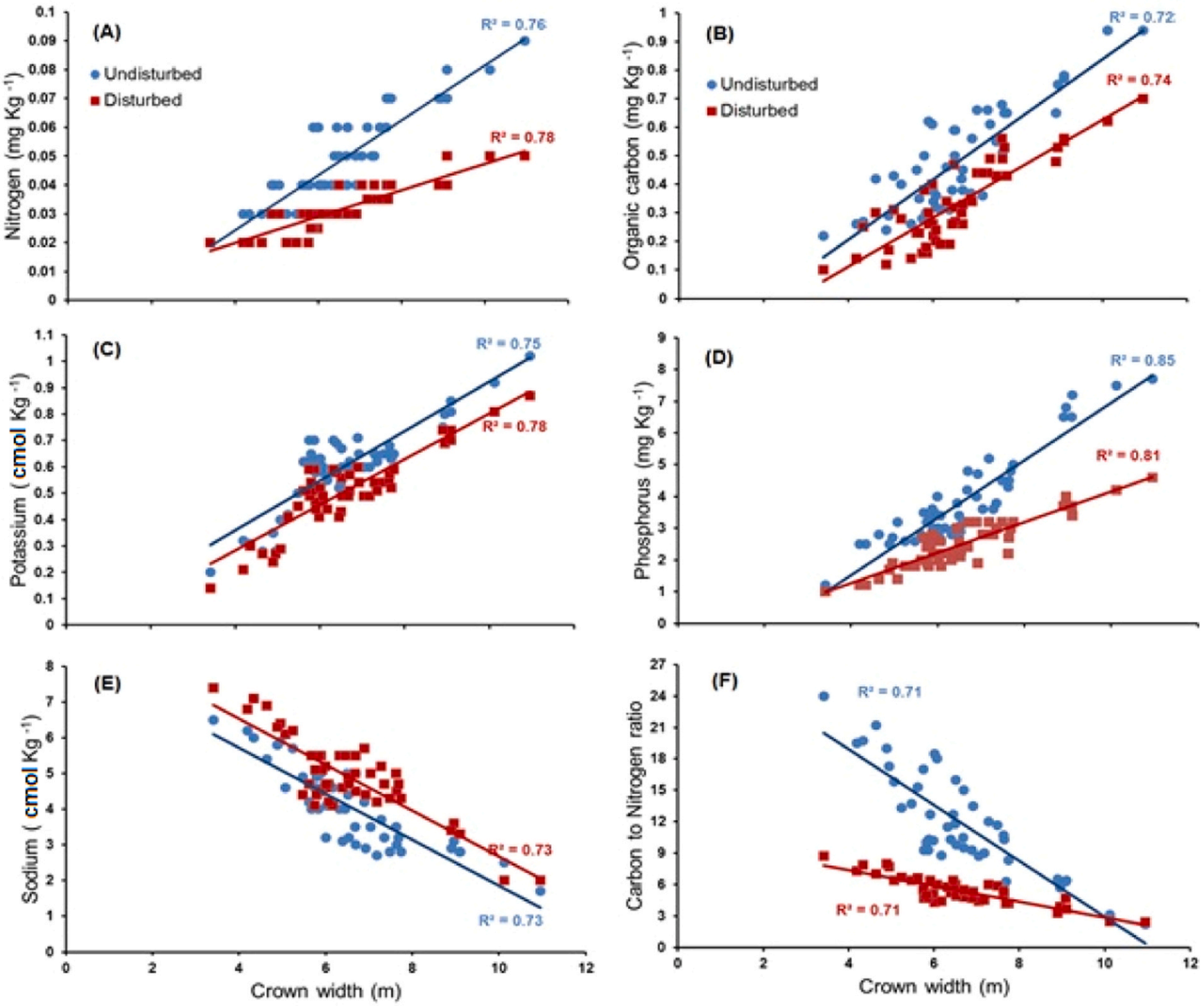

**Fig. 10.** Correlation between the crown width of the adult trees of *B. aegyptiaca* and the (A) soil nitrogen, (B) organic carbon, (C) potassium, (D) phosphorus, (E) sodium, and (F) carbon to nitrogen ratio, in the undisturbed and disturbed sites of Dinder Biosphere Reserve, measured February 2020 to February 2021.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. ELMUGHEIRA M. I. MOHAMMED reports financial support was provided by Rufford Foundation. ELMUGHEIRA M. I. MOHAMMED reports financial support was provided by RUFORUM.

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