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The Ability of Indigenous Legume Trees to Create Islands of Fertility in Extremely Arid & Degraded Ecosystems: Case Study, Al-Kufra Oasis, Libya

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ABSTRACT

This study was conducted in Al-Kufra oasis deep in the Libyan Desert (Sahara Desert). The aim was to evaluate the role of Vachellia nilotica trees in improving soil properties and creating islands of fertility even in a hyper-arid and degraded ecosystem. In three different plots, a systematic sampling procedure consisting of four soil samples collected from each tree from the uppermost layer of the soil (0-30 cm). The first was close to the tree trunk, the second was under the middle of the tree canopy, the third was under the canopy edge, and the fourth was collected from the inter-canopy zone away from the canopy edge. Tree characteristics and crown architecture were investigated for each tree. The study revealed that the mean levels of the examined nutrients in the under-canopy significantly differed from the adjacent inter-canopy zone. Total soil nitrogen, phosphorus, and organic matter contents were significantly higher, and the soil pH values were significantly lower ($p < 0.05$) under than inter-canopy zone. This study illustrated the vital role of indigenous Vachellia nilotica trees in creating islands of fertility and improving soil properties under their canopies over time without any active intervention, even in the hyper-arid and harsh environments as in the Sahara Desert.

الملخص

أجريت هذه الدراسة في واحة الكفرة في عمق الصحراء الليبية، بهدف تقييم قدرة أشجار السنط علي تحسين خصائص التربة وخلق جزر خصبة. أخذت عينات التربة من ثلاث مناطق مختلفة تتواجد فيها أشجار السنط. من تحت كل شجرة في هذه المناطق تم أخذ أربع عينات من الطبقة العلوية للتربة (0-30 سم). الأولى قريبة من الجذع، الثانية تحت منتصف تاج الشجرة، والثالثة تحت حافة التاج، والرابعة من منطقة بعيدًا عن الأشجار، كما تم فحص الخصائص الظاهرية وبنية التاج لكل شجرة. كشفت الدراسة أن متوسط تركيز العناصر الغذائية تحت تيجان الأشجار ترتفع عن المناطق الخالية من الغطاء النباتي. فكان إجمالي محتوى التربة من المغذيات والمادة العضوية أعلى بشكل معنوي ($p < 0.05$)، وكانت قيم الأس الهيدروجيني للتربة أقل بكثير تحت مناطق التاج ($P < 0.05$). أوضحت هذه الدراسة الدور الحيوي لشجرة السنط في تكوين جزر الخصوبة وتحسين خصائص التربة تحت تيجانها حتى في البيئات شديدة الجفاف والمتدهورة كما هو الحال في الصحراء الكبرى.

INTRODUCTION

Vachellia nilotica (L.) P.J.H.Hurter and Mabb. is a legume tree that is native to the Sahara Desert and has a wide range of distribution (Africa, Australia, South America, and Asia). It has adapted to grow on barren lands and dry areas that are not appropriate for many other trees. Thus, it can be found in the tropical, sub-tropical, and Sahara Desert. This plant species is a multipurpose and socially accepted tree because it is providing a lot of functions and a wide range of services (Mugunga and Mugumo 2013).

Taxonomically, *Vachellia nilotica* (L.) P.J.H.Hurter and Mabb. (basionym *Mimosa nilotica* and synonym *Acacia nilotica*) is a flowering evergreen plant tree that belongs to the Fabaceae family according to GBIF Secretariat (2020) and POWO (2020), and it belongs to Mimosaceae according to Jafri and El-Gadi (1978) and APD (2020). It is also known as Egyptian acacia, Egyptian mimosa, Gum arabic-tree, Indian gum-arabic-tree, Babul acacia, black babul, and locally known as 'Gharad'. It is native to Africa, the Middle East, and the Indian subcontinent. Also, it is considered a weed of national significance in Australia (an invasive species of significant concern) (WONS, 2020) as well as a federal noxious weed in the United States (NRCS, 2020). This plant species is a moderately long-lived tree and can withstand extremely arid environments and endure floods.

Farmers keep this kind of trees on their farmlands and near their houses, mainly, for fuelwood production, farm tools, gum, local medicine, constructions, and animal fodder where natural grazing vegetation is rare. (Alshareef and Alaib, 2018; Birhane *et al*., 2019; Pandey and Sharma, 2003). Besides, they are used for sand-dune stabilization, wind-breaking, and can provide shade and fresh air for people and shelter to soils, plants, livestock, and wild fauna (Mohamed *et al.*, 2000; Alharathy, 2020).

V. nilotica is amongst those plants adapted to live in a hyper-arid environment such as the Sahara Desert. It is found in many areas in the Libyan Sahara; from Al-Awaynat Mountain in the southeast of the country to Al-Haruj in the middle of the Sahara to Sabha desert city and extended to the southwest to Ghat oasis by the Algerian border. Similar species of legume trees that are existed in different parts of Libya include *Acacia saligna* (Labill.) H.L.Wendl. (synonym *Acacia cyanophylla*), *Vachellia karroo* (Hayne) Banfi and Galasso (synonym *Acacia karroo*), *Vachellia tortilis* subsp. *raddiana* (Savi) Kyal. and Boatwr. (synonym *Acacia tortilis* subsp. *raddiana*), and *Acacia cyclops* A.Cunn. ex. Don.

Some of these species are non-indigenous; they were introduced from Australia, South Africa, or Sudan (Keith, 1965). The most common species in Libya are *Acacia saligna* and *Vachellia karroo*. These two species are widespread and cultivated throughout the country, mainly for stabilizing soils and building wind-breaks. *Vachellia karroo* is cultivated around the farms to form an impenetrable barrier to livestock (Mohamed *et al.,* 2000).

Faidherbia albida (Delile) A.Chev. (Basionym *Acacia albida* Delile) and *Vachellia farnesiana* (L.) Wight and Arn. (synonym *Acacia farnesiana*) can occur, but usually in scattered and limited numbers (Jafri and El-Gadi 1978). *Vachellia nilotica* and *Vachellia tortilis* subsp. *Raddiana* are indigenous species to Libya and grow naturally in the southern part of Libya. *Acacia cyclops* is restricted to the northern region of the country by the Mediterranean coast, growing in the areas subjected to sea winds (Mohamed *et al.,* 2000).

Several other species of *Acacia* trees were also introduced to Libya (Jafari and El-Gadi, 1978), but not widely distributed, such as *Acacia pycnantha* Benth. (Edrah *et al.,* 2018).

Pampanini (1930) also mentioned *Vachellia nilotica* subsp. *nilotica* (synonym *Acacia arabica*).

Such legume trees, including many species of *Vachellia* and *Acacia* species, are amongst the essential components of the Sahara ecosystem and play a significant ecological and economic role (Belsky *et al.,* 1993; Ludwig *et al.,* 2004; Hagos and Smit, 2005; Birhane *et al.,* 2019). These trees have a strong ability to modify soil properties and improve soil fertility (Palm 1995), hence enhance ecosystem dynamics (El Atta *et al.,* 2013). The nitrogen (N) fixing ability of the root-nodules makes these trees amongst the most preferred species for agricultural fields (Puri *et al.,* 1994) and degraded lands. These plant species can accumulate nutrients and initiates areas containing higher nutrient concentration under their canopies (Pandey *et al.,* 2000). Being perennial, the tree function and influence on the soil increase over time (Mugunga and Mugumo, 2013). In addition to increasing soil nutrient content, dropping organic litter in such arid areas buildup soil aggregation, resulting in more soil stability against erosion, improving microbial biomass and activity, and developing soil structure texture (Pandey *et al.,* 2000).

Nutrient levels under trees are accumulated and enriched over time, especially in arid and semi-arid environments (e.g., Ludwig *et al.,* 2004; Sitters *et al.,* 2013), by the dropping and decomposition of tree litter (Fterich *et al.,* 2012; De Boever *et al.,* 2015), animal dung and excretion (Deans *et al.,* 1999; Allington and Valone, 2014), minerals mining by tree roots (Belsky, 1994; Wilson *et al.,* 2007) and thru capturing and retaining of soil particles and minerals by tree bodies during aeolian and hydrologic processes like wind erosion and water run-off (Schlesinger *et al.,* 1998; De Boever *et al.,* 2015). Therefore, soils under tree canopies become more fertile and stable than the adjacent inter-canopy areas.

Previous studies in various worldwide ecosystems have revealed that nitrogen-fixing trees tend to increase soil content of nitrogen (N) and organic matter (SOM), in addition to other nutrients (Belsky *et al.,* 1993; Nair, 1993; Palm, 1995; Young, 1997; Pandey *et al.,* 2000; Pandey and Sharma, 2003; Ludwig *et al.,* 2004; Hagos and Smit, 2005; Sitters *et al.,* 2013; Alshareef and Alaib, 2018). These trees display reciprocal association with the *Rhizobium* bacteria that live in their root-nodules. The bacteria are benefited from the shelter, moisture, and carbohydrates in the root-nodules, and in turn, supply the tree with nitrogen by fixing atmospheric nitrites to nitrates (Daniel *et al.,* 2018). As a result, these trees are capable of significantly enriching soil with N and add more SOM. Over time the soil's chemical and physical properties are improved (El Atta *et al.,* 2013; Birhane *et al.,* 2019). This has been well established in various ecosystems, as in North Africa (De Boever *et al.,* 2015), African Savanna (Scholes, 1990; Belsky, 1994; Deans *et al.,* 1999), Australia (Tiessen *et al.,* 2003), and Brazil (Wilson, 2002). However, much less is known about their role in hyper-arid ecosystems. It has not been investigated in detail under local conditions in the Libyan Desert (rainfall < 100 mm/y and evapotranspiration > 2000 mm/y). Also, there is a great need to identify suitable N-fixing plants; those can thrive well during the process of stabilization and recovery of degraded sites in the arid and hyper-arid ecosystems in the Libyan Desert.

Hence, this study attempted to fill the gap concerning the ecological role of the Libyan Desert's legume trees, and we picked up *V. nilotica* trees to be subject to the present study as it is amongst the remaining few native trees that still be found in the Sahara Desert. Therefore, we were interested in investigating their biomass size and its capability to stabilize nutrients and accumulate SOM, thus creating islands of fertility and improving the soil under their canopies in this hyper-arid ecosystem.

MATERIALS AND METHODS

Study Area

The study was conducted in El-Kufra Oasis, located deep in the south-eastern part of the Libyan Desert between latitudes 24° 00' – 24° 20' N and longitudes 23° 00' – 23° 40' E (Fig. 1). The Libyan Desert is constituting a large part of the great Sahara Desert. The ground altitude ranging between 371 – 426 meters above sea level, and the general slope of the ground surface is 1.3% towards the north direction. In general, El-Kufra area is a typical desert environment representing the hyper-arid climate of the Sahara Desert.

Soils in the study area are arid and undeveloped Sahara soils. They are relatively uniform and unstructured, consisting mainly of sandy soil with little organic matter content and deficient in nutrients due to the absence of vegetation. Generally, the soil pH ranging from 7 to 8 (El-Barasi *et al.,* 2009; Mohamed *et al.*, 2000).

For 112 years of meteorological data analysis, the main climatic feature is hyper-arid with a mean rainfall of 3.1 mm/y and a mean annual number of rainy days of only 1.3 days/y (Wheatherbase, 2020); many years may pass without any drop of rain. The mean annual temperature is 23.4°C, and the mean minimum and maximum annual temperatures are of 15.3°C and 30.4°C, respectively (Fig 2). The average air relative humidity ranges between 24% in summer (June) and 47.6% in winter (December) with a mean annual value of 34%. In these hyper-arid environments, the mist and dew are considered a more important moisture source than rainfall. This part of the Sahara Desert is one of the driest ecosystems worldwide.

Generally, the ground surface of the Libyan Desert is free from any plants. The vegetation frame consists mainly of scattered xerophytic plants in some valleys (dry rivers), around some oases, and in low-lying lands where the underground water is reachable, particularly at the southern fringe of the Sahara. *V. nilotica* is amongst a few tree species that exist in this part of the Sahara consisting one of the few and scattered woodlots in the area. After rainy events, which are very rare, the area might be covered with a carpet of ephemeral plants, particularly in valley beds and low-lying lands, which received more moisture throw run-off and subsurface water movement.

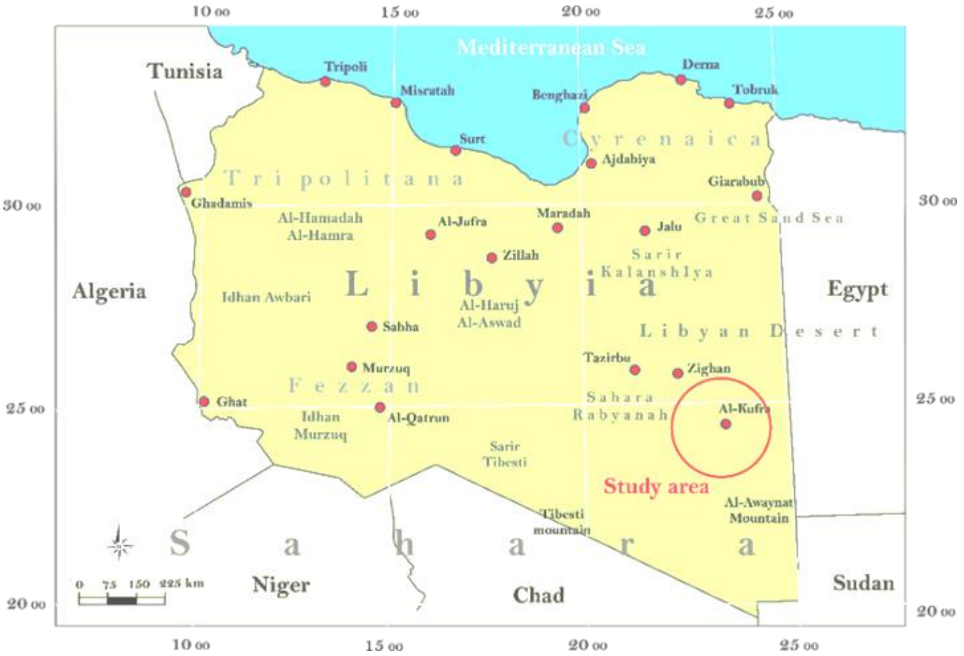

Fig 1. Map showing the geographical location of the study area (El-Kufra area, the south-eastern part of Libya deep in the Sahara Desert).

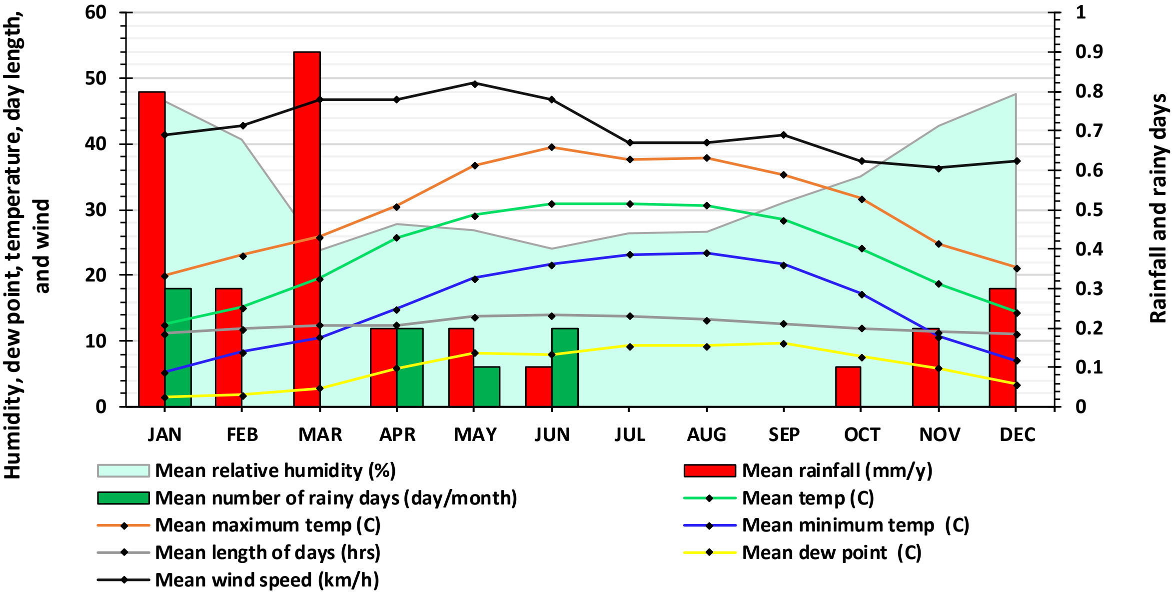

Fig 2. The climatic diagram for Al-Kufra Oasis as acquired from Wheatherbase web site (Wheatherbase, 2020) for the El-Taj meteorological station, elevation = 378 meters above sea level, and at coordinates; 24° 12' N and 23° 17' E. For a 112-year record.

Experimental design

Three different plots of *V. nilotica* tree were chosen randomly to conduct the present study. First, tree characteristics and crown architecture such as total tree height, height to the canopy, and width and breadth were measured. Then, soil pH, soil organic matter (SOM), and total-macro-nutrient contents [nitrogen (N), phosphorus (P), and potassium (K)] were examined. The soil samples were collected from the topsoil layer (0-30 cm) along a transect line extending from the base of the tree trunk under-canopy (tree crown zone) to the barren outside area at least 50 meters away from the nearest canopy edge (inter-canopy zone). We only sampled the topsoil layer as nutrients in this layer are highly influenced by the accumulation and decomposition of organic matter from tree leaves, stems, roots, and animal droppings. Before sampling, we removed the above-ground litter layer. For each tree, there were four different sampling sites; beside the tree trunk, middle of the canopy, canopy edge, and from the inter-canopy area. Samples were put in sealed plastic bags and transferred to the lab for chemical and physical analysis.

Soil Analyses

In the lab, soil samples were air-dried for 72 hours then passed through 2 mm sieve mesh. Soil pH was determined with a direct-reading of a pH-meter in soil suspension (1 part soil: 2.5 parts of deionized water) according to Rayment and Higginson (1992) after calibrating the device using different buffer solutions (pH = 4, 7, and 10). Total soil-N content was determined following the Kjeldahl method using Gerhardt Protein and Nitrogen Analysis machine. Total soil-K was determined by atomic absorption method using Thermo Scientific - SOLAAR M Series AA Spectrometer machine. Total soil-P was determined by spectrophotometer method using AquaMate Plus machine. After heating the samples in an oven for 24 hours at 105°C to exclude soil moisture, the SOM was determined by soil ignition for 8 hours at 400°C according to Schulte and Hopkins (1996) using Carbolite SWF 1200 furnace.

Statistical analyses

All data were statistically analyzed. Initially, the data were verified and tabulated in a Microsoft Office Excel spreadsheet (Microsoft Corporation-2019) and then were subject to descriptive analysis and normality distribution test. Variance test (T-test and One-Way ANOVA) were applied, then followed by Post Hoc Test (Tuckey HSD) to assess the differences between and among the different treatments. In the pH case, Mann-Whitney and Kruskal-Wallis H tests were applied because the pH data have non-normal distribution. All statistical significances were determined at a significant level (*p*-value) of ≤ 0.05. All analyses were performed using IBM SPSS Statistics software (version 26).

RESULTS AND DISCUSSION

Soil properties are a critical factor influencing ecosystem functionality and productivity; mainly, it is an essential driver of plant existence, growth, and persistence (El Atta *et al.,* 2013). Spatial heterogeneity in the availability of soil resources (e.g., moisture, nutrients, organic matter) and chemical and physical properties (e.g., pH, EC, bulk density, texture) influencing the shape and structure of plant community (Jones and Callaway, 2007; De Boever *et al.,* 2015). This is more obvious in arid zones because the availability of soil nutrients and moisture can be very limited (Saltz *et al.,* 1999).

On the other hand, the interactions amongst biological, chemical, and physical processes in the soil in time and space determine the soil properties and fertility level (Pandey *et al.,* 2000). Development of soil characteristics and fertility is primarily a consequence of increasing organic matter inputs, nutrient recycling, protection against erosion, and N-fixation, which is mainly dependent on legume plants (Nair, 1993; Palm, 1995; Pandey *et al.,* 2000). Many legume trees, e.g., *Vachellia* species, have been shown to create prominent alterations over time in the below- and above-ground ecological processes, e.g., community structure, microclimate condition, soil moisture content, and soil nutrient concentration and availability (Le Maitre *et al.,* 2011), which in turn increase soil fertility and improve soil characteristics.

Tree architectural characteristics

From our field measurements, *V. nilotica* trees in the study area were not very high (mean = 6.75 m), but have shown a big crown size (mean canopy height 'without the trunk' = 4 m, width = 21.5 m, and breadth = 12 m). This leads to big flattened crowns take an umbrella shape with a strong shading effect (Table 1). These such big architectural characteristics of the tree's crown could be an indication of the old life of these trees and, also, cause a more dropping of dead branches and leaves which over time build up a higher proportion of soil organic matter and enhance the pool of nutrients under the tree canopy (Pandey *et al.,* 2000). Generally, tree litter comprises a major portion of soil organic matter and enhances the activity of enzymes in soil, thus, improve soil fertility including the availability of macro-nutrients (El Atta *et al.,* 2013).

As observed in the field, all trees in the study area were mature, and no new seedlings were observed. Furthermore, in all the surveyed plots, no other plant species were noticed in the under-canopy or vicinity areas of the *V. nilotica* trees. This is maybe attributed to the hyper-arid climate and, also, to the highly competitive behaviour (De Boever *et al.,* 2015) and the allelopathy effect of the *V. nilotica* trees. Which suppresses vegetation succession and seed germination (Moyo and Fatunbi, 2010) even for the same *Vachellia* species.

Soil nitrogen content

The ability of *V. nilotica* tree species to fix atmospheric N and increase its concentration in soil, through symbiosis process by the cooperation with *Rhizobium* bacteria and vascular arbuscular *mycorrhizal* fungi, is a major factor for N fertilization of poor soils

(Daniel *et al.*, 2018), particularly in arid ecosystems. Soil-N is a crucial plant nutrient because it is essential for creating almost all plant structures, including proteins, enzymes, chlorophyll, and many others (Hooper and Johnson, 1999). Therefore, it is a vital element for the growth and regeneration of plants (Krapp, 2015). Consequently, plants require a higher amount of N relative to other macro-nutrient elements (Daniel *et al.*, 2018).

The present study results indicated that the soil-N content in the study area was very low (mean = 55.1 ppm ± 9.51 SE), this is due to the arid climate, and the area is lacking in vegetation cover. Low soil-N availability decreases primary productivity and seed production, especially for desert plants (Drenovsky and Richards, 2004).

Nevertheless, the soil-N content was significantly higher in the under-canopy of *V. nilotica* than the inter-canopy areas ($t(10) = 2.549$, p-value = 0.029); the increased ratio was about 320% (Table 2 and Fig 3). This is mainly attributed to the accumulation of organic litter from dead leaves, branches, roots, and the trees' ability to fix atmospheric nitrogen. This result consistent with the finding of many studies in various ecosystems elsewhere (e.g., Belsky *et al.*, 1989; Schlesinger and Pilmanis, 1998; Yang *et al.*, 2011; Allington and Valone, 2014; Daniel *et al.*, 2018).

Although the Sahara Desert is a hyper-arid region, the *V. nilotica* trees play the same role as in the other tropic and sub-tropic regions in fixing and increasing soil-N content and improving soil fertility. This supports the assumption that legume plants in various ecosystems affect the soils in a comparable performance (Belsky *et al.*, 1989).

Table 1. Mean values and Std Error for tree architectural characteristics in the study area.

Total tree height (m)	Trunk Height (m)	Canopy height (m)	Canopy width (m)	Canopy breadth (m)
6.75 (± 1.25)	2.75 (± 0.25)	4 (± 1.00)	21.5 (± 3.00)	12.05 (± 0.95)

The highest mean value of soil-N content was recorded at the middle of the canopy (96.99 ± 12.83 SE) then at the canopy edge (62.50 ± 12.99 SE). The significant level amongst the different sampling sites (beside tree trunk, middle of the canopy, canopy edge, and inter-canopy zone) was very high (p-value = 0.003) (Table 3 and Fig 4).

Table 2. Mean, Std. Error, and significance level (p-value) for the concentration of the measured soil-parameters in under- and inter-canopy zones of *Vachellia nilotica* trees in the study area.

Parameter	Under-canopy zone		Inter-canopy zone		p-value
	Mean	Std. Error	Mean	Std. Error	
Nitrogen (ppm)	66.50	± 10.02	20.77	± 1.14	0.029
Phosphorus (ppm)	3.27	± 0.31	1.68	± 0.31	0.020
Potassium (ppm)	88.26	± 16.79	40.93	± 11.00	0.153
Organic matter (%)	0.75	± 0.04	0.51	± 0.09	0.013
pH	6.37	± 0.06	6.97	± 0.48	0.054

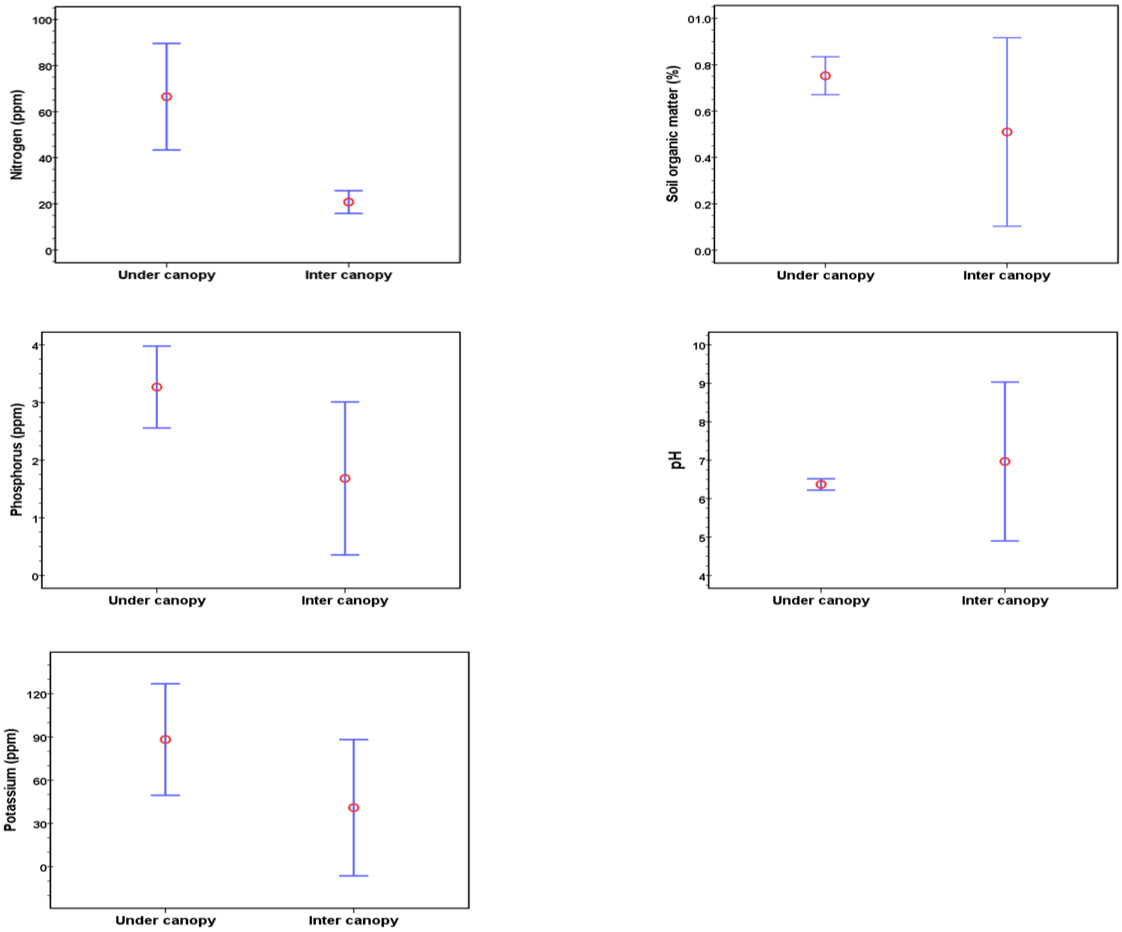

Fig 3. The concentration differences in the measured soil-parameters (N, P, K, SOM, and pH) between under- and inter-canopy zones of the *Vachellia nilotica* trees in the study area.

Table 3. Mean, Std. Error, and significance level (*p*-value) for the concentration of the measured soil-parameters in a transect line from the tree trunk to the area outside the tree canopy (inter-canopy) of the *Vachellia nilotica* trees in the study area.

Parameter	Beside trunk	Middle canopy	Canopy edge	Inter-canopy	*p*-value
Nitrogen (ppm)	40.00 (6.93 ± SE)	96.99 (12.83 ± SE)	62.50 (12.99 ± SE)	20.77 (1.14 ± SE)	0.003
Phosphorus (ppm)	2.34 (0.57 ± SE)	3.69 (0.27 ± SE)	3.79 (0.29 ± SE)	1.68 (0.31 ± SE)	0.011
Potassium (ppm)	118.22 (41.02 ± SE)	44.77 (5.53 ± SE)	101.78 (13.56 ± SE)	40.93 (11.00 ± SE)	0.091
Organic matter (%)	0.77 (0.04 ± SE)	0.65 (0.05 ± SE)	0.84 (0.05 ± SE)	0.51 (0.09 ± SE)	0.025
pH	6.26 (0.12 ± SE)	6.58 (0.01 ± SE)	6.27 (0.04 ± SE)	6.97 (0.48 ± SE)	0.223

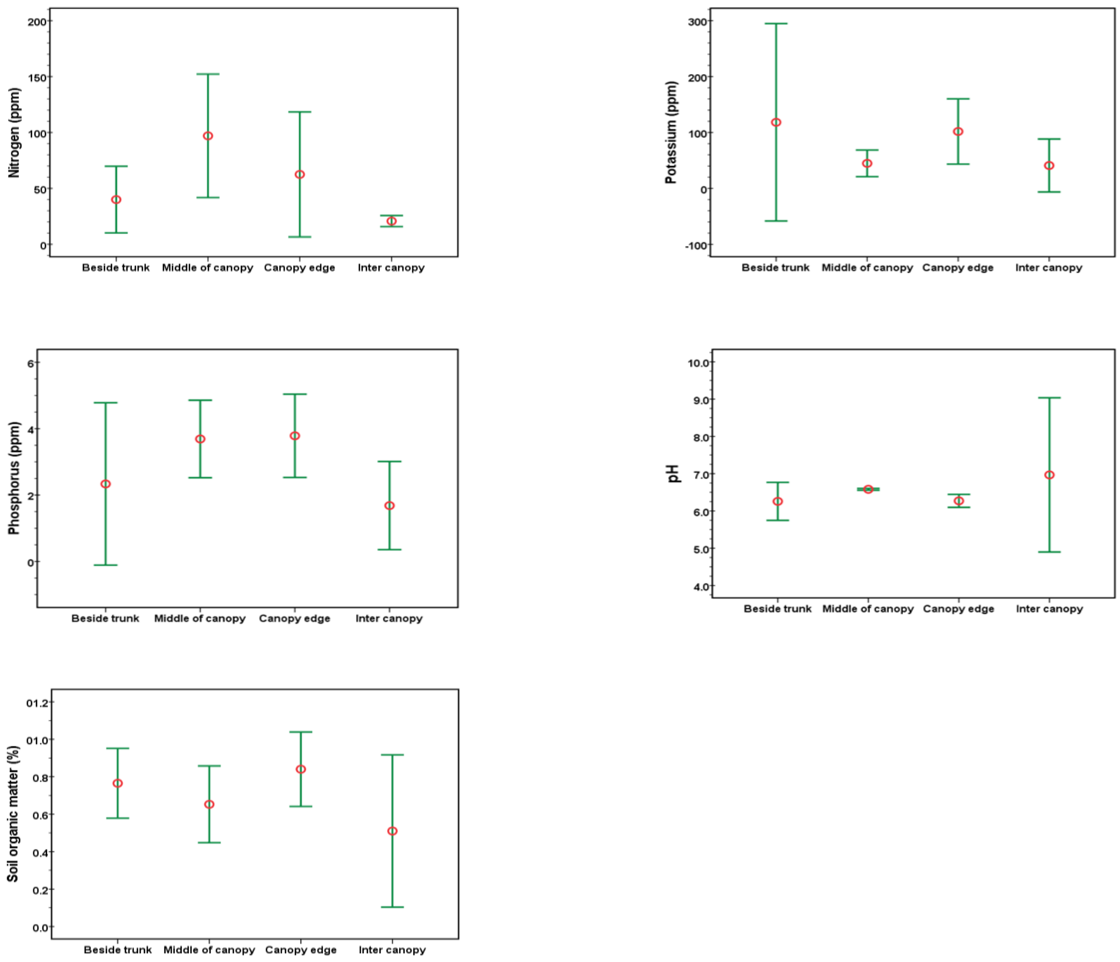

Fig 4. The concentration differences in the measured soil-parameters (N, P, K, SOM, and pH) along a transect line from the tree trunk to the open area away from the tree canopy (inter-canopy zone) of the *Vachellia nilotica* trees in the study area.

Soil phosphorus content

The soil-P content in this study was very low as well (mean = 2.87 ppm ± 0.31 SE). This is most likely due to the Sandy soil texture, which is deficient in nutrients content. However, this study demonstrated a significantly higher content of Soil-P under tree canopies ($t(10)$, p-value = 0.020); the increased ratio was about 195%. The highest mean soil-P content was recorded at the canopy edge (3.79 ± 0.29 SE) then at the middle canopy (3.69 ± 0.27 SE), with a significant difference amongst the different sampling sites (p-value = 0.011) (Table 3 and Fig 4).

The trees that grow in such arid and poor soils are forced to spread their roots widely in both horizontal and vertical directions; to get more moisture and nutrients. By using this mechanism, the trees try to meet their needs of nutrients as P, which returned to the under-canopy soil through dead leaves, branches, and roots (Sitters *et al.*, 2013). Studies in various ecosystems pointed out that the plants with deep roots can obtain a considerable amount of their nutrient needs, specifically P, from the deep ground layer (Sitters *et al.*, 2013), which consequently accumulated in the topsoil layer under the tree canopy.

The significantly higher soil-P content in the under-canopy zone of the *V. nilotica* in this study consistent with the findings of Rothauge *et al.,* (2003), who found higher soil-P content under the canopy of *Vachellia erioloba* tree than the adjacent inter-canopy zones in South African Savanna. On the other hand, our results contrast with the previous finding of Sitters *et al.* (2013) for *Vachellia zanzibarica* tree in Saadani National Park located in a Savanna area in Tanzania, where their results showed no decline in soil-P content beyond the tree canopy. This may be attributed to the dense vegetation existence in the areas between tree canopies in the Savanna; meanwhile, there are no plants in our study area rather than the scattered *V. nilotica* trees.

Even though there was an increase in N and P in the soils under the canopy of *V. nilotica* trees, the relative content of N to P did not increase at the same rate. This could be recognized when we look at the N/P ratio in the under-canopy zone (N/P = 20.3), which was higher than the inter-canopy zones (N/P = 12.4). This illustrated that the addition rate of N is more than that for P by a ratio of 164%. This is most likely due to the efficiency of *V. nilotica* in fixing and accumulating N is much higher than the accumulation of P due to the low content of P in the different layers of the soil in this hyper-arid area.

Soil potassium content

As for N and P, the soil-K content was, in general, very low as well (mean = 76.4 ppm ± 4.1 SE). Even though the soil-K content under-canopy was higher than the inter-canopy zones with a ratio of 216%, there was no significant difference detected between them ($t(10) = 1.548$, p-value = 0.153) (Table 2 and fig 3). This result consistent, to some extent, with Treydta *et al.*'s (2013) finding in the African savannas, who found significantly higher N, K, and P contents in the under-canopy zone.

For soil-K content along a transect line from tree trunk to inter-canopy areas, the K content had a different trend than N and P, as the highest mean value was recorded beside tree trunk (118.22 ± 41.02 SE) then at canopy edge (101.78 ± 13.56 SE). No significant difference was detected amongst the different sampling sites (Table 3 and Fig 4).

The increase in soil-K content under-canopy areas in our study is mainly attributed to the decomposition of dead tree parts after falling on the ground surface underneath the trees. It may also be related to the low leaching effect due to the low rainfall in amount and events, which led to the accumulation of the K in the topsoil layer. This could also be valid for the increased content of other soil nutrients (e.g., N, P).

Potassium is vital for plants, especially in arid environments. It enhances plant survival mainly due to its effect on the osmotic adjustments and the reduction in transpiration rates from plant leaves, which in turn resulted in higher efficiency of using the available water by the plant (Gómez-Aparicio *et al.,* 2005).

Soil organic matter content

Similarly, the soil content of SOM was very low (mean = 0.69% ± 0.05 SE). This is a general character of the Sahara soils (El-Barasi *et al.,* 2009) due to the lack of vegetation cover. However, the SOM was significantly higher under the canopy when compared to the inter-canopy areas ($t(10) = 3.026$, p-value = 0.013). The under-canopy increase is about 147% times than the inter-canopy areas (Table 2 and Fig. 3). This is mainly attributed to the absence of vegetation outside the canopy zone and the continuous accumulation of dead leaves and roots overtime under the tree canopy, in addition to the dropping of fauna excretion that uses these trees as fodder or shelter. This corresponded with the finding of many studies in other arid and semi-arid environments (e.g., Pandey *et al.,* 2000; El Atta *et al.,* 2013).

The highest mean SOM content was recorded at the canopy edge (0.84 ± 0.05 SE) then beside the tree trunk (0.77 ± 0.04 SE), with a significant difference amongst the different sampling sites (p-value = 0.025) (Table 3 and Fig 4).

The higher SOM content under-canopy is deemed to have a substantial positive effect on many other soil characteristics (Harden and

Mathews 2000; Li and Shao 2006; Daniel *et al.*, 2018). This is evident by an increase in nutrient content (N, P, K) and ameliorating soil pH, as explained below, compared to the inter-canopy soils. The higher soil organic matter in the under-canopy soils increases inter-particle bonding and soil stability, reduces soil erosion, and increases microbial biomass and nutrient availability (Knoepp *et al.*, 2000; Lechmere-Oertel *et al.*, 2005). The increased soil organic matter also enhances soil porosity and water infiltration rate, and increases water-retention-capacity of the soil in such hyper-arid areas, particularly in sandy soils (De Boever *et al.*, 2016).

The N/SOM ratio was higher under-canopy of *V. nilotica* trees (N/SOM = 88.7) than in the inter-canopy zones (N/SOM = 40.7). This revealed that the N-fixation rate in the soil under-canopy is much higher than the accumulation of SOM, as also stated above for the N/P ratio. Many scholars suggested that the primary constraint on SOM accumulation is N-limitation (Sitters *et al.*, 2013), but this was not the case in this hyper-arid environment as in the study area. This is most likely due to the moisture deficiency in these hyper-arid environments that play a significant constraint role in tree biomass production even though there is relatively substantial soil-N content for tree growth.

Soil pH

The soil in the study area is mainly an undeveloped dry sandy soil; consequently, it lacks element content. This is reflected in a more neutral soil pH (mean = 6.5 ± 0.14 SE) (Table 2 and Fig 3). The results were very similar among the soil pH values, and no significant difference was detected amongst the sampling sites. The highest mean value was recorded at the inter-canopy zone (6.97 ± 0.48 SE) then at the middle canopy (6.58 ± 0.01 SE).

Soil pH value determines nutrient availability; most nutrients require specific pH values to be available for plant roots. The high values of soil pH is an indication of infertility because it affects the availability of P, N, and many other macro and micronutrients, which substantially decrease (i.e., become less soluble) above a pH value of seven (Lechmere-Oertel *et al.*, 2005; Bonanomi *et al.*, 2008).

Trees capture and return leached nutrients in the soil's upper layer through processes known as the nutrient pump and the safety net. In doing so, trees can affect soil pH by reducing or increasing it depending on tree species (Mugunga and Mugumo 2013), climatic conditions, and associated vegetation. In the present study, the mean pH value was significantly lower in under- than inter-canopy zone ($t(10) = -2.187$, p-value = 0.054) (Table 2 and Fig. 3). This consistent with the finding of Deng *et al.*, (2017) about the effect of Acacia trees on the soil pH in South Sudan, and with the finding of Ryan and McGarity (1983) for the Eucalypts trees effect on soil pH in Australia. At the same time, this contrasted the findings of other studies (e.g., Hagos and Smit 2004; Birhane *et al.*, 2019), who showed no significant effect of the Acacia trees canopy on soil pH between under- and inter-canopy zones in northwestern Ethiopia. Other studies (e.g., El Atta *et al.*, 2013; Mugunga and Mugumo, 2013) showed a highly significant increase of pH values under Acacia tree canopies than in the inter-canopy zone in Saudi Arabia and Rwanda. The different effects of the tree canopy on some soil properties, e.g., pH, may be related to the variation of climate conditions and other environmental factors in the various areas covered by the mentioned studies; e.g., rainfall amount and regime, and the structure and composition of the associated vegetation.

Although there were significant differences in the spatial concentration in most of the measured soil parameters between under- and inter-canopy zones in this study, the concentration of the different nutrients distributes randomly in the various sampling sites along a transect line from tree trunk to inter-canopy zone, and there was no similar trend for all of the measured parameters. This contrasted some previous studies (e.g., Belsky

1994; Ludwig *et al.,* 2004; De Boever *et al.,* 2015), which have shown a constant increase in nutrient content from the inter-canopy zone towards the tree trunk.

CONCLUSION

The present study suggests that the *V. nilotica* trees, with their big crown shape, long persistent age, and incredible adaptability to the arid climate, are capable of creating islands of fertility even in hyper-arid areas as in the Sahara Desert. These trees increase organic matter by dropping litter, fix N by root symbiotic nodules, and accumulating other nutrients by transporting them from deep and subsurface soil layers of the surrounding areas. Also, the dropping and excretion of various fauna species that use these trees as a fodder source or shelter contribute significantly to this process over the trees' lifetime. Of all the factors studied, the most prominent indicators of the existence of islands of fertility were N, P, and organic matter, in addition to the improvement of other soil chemical and physical properties, e.g., pH.

The findings of this study illuminate the ability of some indigenous tree species in the Sahara Desert to improve the poor soils naturally in these hyper-arid ecosystems. We just need to protect these trees and increase their numbers by protecting their local environment. However, the remaining unanswered questions in this study that need further investigation are: what is the primary resource of nutrient enrichment in the soil under the canopy of *Vachellia nilotica* trees in this hyper-arid environment? Is it the dead leaves and roots, bird droppings, or animal excretion and dung? Furthermore, why the distribution under the tree canopy along a transect line from the canopy edge to the tree trunk is not the same for all the nutrients?

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STATEMENT ON CONFLICTS OF INTERESTS

The authors have no conflict of interest in relation to this work.

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