Research Article

The Effects of Mesquite (Prosopis juliflora) on Soils and Plant Communities in the Deserted Rangelands of Bahrain

Manal A. M. Sadeq,1 Mohammed S. Abido,1 Ahmed A. Salih,2 and Jameel A. Alkhuzai3

1Natural Resources & Environment Department, Arabian Gulf University, P.O. Box 26671, Manama, Bahrain
2Khartoum North Nabatah, Block 2, No. 196, Khartoum, Sudan
3No. 2149, Road 2958, Block 729, Jurdab, Bahrain

Correspondence should be addressed to Mohammed S. Abido; mohammedsaa@agu.edu.bh

Received 3 April 2020; Revised 8 July 2020; Accepted 23 July 2020; Published 19 August 2020

Copyright © 2020 Manal A. M. Sadeq et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The influence of mesquite trees (Prosopis juliflora (Swartz) D.C.) on the physicochemical properties of soils and annual understory plants was investigated in the deserted rangelands of Bahrain. Soil properties were measured in the understory and the uncanopied adjacent areas of mesquite trees. Likewise, the number of plant species was assessed in four 1 × 1 m randomly distributed quadrates in the understory and the uncanopied adjacent areas. The results showed that sand particles exceed 96% of soil composition. Soil bulk density at the 0–5 cm soil depth was significantly higher in the understory of trees compared to the uncanopied adjacent areas. However, moisture at a depth of 40–60 cm was significantly higher in the uncanopied adjacent areas. No differences in the pH, EC, K, Na, and Ca were found between understory and the uncanopied areas in all soil depths. Levels of N, P, Mg, and organic matter were significantly higher in the understory of trees compared to the uncanopied adjacent areas. Organic matter was twice the amount in the upper 20 cm of soil layers in the understory of mesquite trees. Species richness did not differ between the understory and the uncanopied areas. Nevertheless, the density of ephemerals in the understory of mesquite trees was higher than the uncanopied areas by 18%. The Shannon-Weaver index of diversity was higher in the uncanopied areas compared to the understory. The study concluded that the canopy effects of mesquite trees on soil vary with depth. Nonetheless, the influence of mesquite on flora could be beneficial for annual understory plants but subject to many operating factors, including density and cover of mesquite trees.

1. Introduction

Worldwide, invasive alien species are considered as direct drivers of ecological change and biodiversity decline [1, 2]. These species cause damage to the environment and human health. They function as agents of change that influence other species, habitats, and ecosystems [3]. Prosopis juliflora (Swartz) D.C., commonly known as mesquite, is one of the species that is reported to be invasive in many regions of the world [4]. It is an evergreen tree belonging to the Leguminosae family. Mesquite is a nitrogen-fixing species [5] and thrives in low rainfall and high-temperature areas. It grows on compacted soils or soils with hardpans, tolerates saline soil, and efficiently extracts soil water [6, 7].

The species was introduced into Bahrain for landscaping and amenity purposes in the 1930s. The oldest specimen of the species, which is believed to be 500 years old, locally known as the “Tree of Life,” is considered a focal point in the landscape of Bahrain [8]. Mesquite trees are naturalized and widely planted in towns and villages of Bahrain. Recently, mesquite trees have been sighted along drainage canals, agricultural farms, and deserted rangelands as well as abandoned farms in the country.

Several authors studied the influence of mesquite trees on soil properties [9–12]. Nonetheless, such an effect was linked to other relevant factors, including climate, soil properties, canopy density, and plant coverage [13]. For instance, Tiedemann and Klemmedson [10] and Deans et al.
[14] stated that surface soils under crowns of *Prosopis* spp. were more fertile than soils in the adjacent areas. Likewise, several scholars [15–17] highlighted the positive effects of mesquite on organic matter and nutrient contents of the soils.

On the other hand, adverse effects of mesquite on biodiversity and ecosystems including rangelands, pastures, wetlands, and native flora have been controversial [4, 18–21]. In this respect, Mukherjee et al. [22] reported that mesquite is demising dominant native species over a long time. El-Keblawy and Al-Rawai [16] and El-Keblawy and Abdelfatah [19] stated that associated plant communities were negatively affected under the canopies of mesquite trees, and the magnitude of the effect was dependent on the size and density of the trees. On the contrary, Naudiyal et al. [23] indicated that *P. juliflora* canopy had a little effect on local flora, and mesquite facilitated the regeneration of native species under its canopy.

The effect of mesquite trees on soil properties and understory plants has been altered by many parameters including the climate of the region [24], vegetation types [25], stand attributes [16], and soil properties [17]. Conceivably, mesquite invasion and its threat mechanism to different habitats and flora in Bahrain are neither known nor documented. There is a need to understand the process of mesquite invasion, the extent of its colonization, impacts, interactions, and analysis of the risk associated with its spread. The objective of this study is to determine the influence of *P. juliflora* on soil properties and annual understory plants in the sandy ecosystems of Bahrain.

### 2. Materials and Methods

#### 2.1. Study Area

Bahrain is an archipelago of 36 islands occupying a total land area of 779.39 km². It is located between latitude 25°32′ and 26°20′ north and longitude 50°20′ and 50°30′ east. The study area is chosen to be in the middle of one of the largest mesquite stands in the country at 26°10′20″N and 50°29′36″E (Figure 1). The environment is arid to extremely arid with mean annual temperature and precipitation of 26.8°C and 99.8mm, respectively. Rainfall is erratic and occurs in winter only while aridity (T) prevails all year long [26] (Figure 2). The mean daily evaporation rate ranges from 3.5 mm in January to 15.6 mm in June. The soils are shallow, poorly defined in the structure, and mostly underlain by sand or a cemented layer of the gypsic or calcic horizon [27]. Major soil groups include Solonchaks, Regosols, Yermosols, and Fluvisols [28].

#### 2.2. Soil Analysis

Soil samples were collected from the understory (2m from the main stem of the tree) of four randomly distributed mesquite trees and the uncapped adjacent areas (2m distance from the edge of the tree crown). A core was taken at four depths of 0–5, 5–20, 20–40, and 40–60 cm in four replicates. The samples were air-dried and passed through a 2 mm sieve. Bulk density (BD) (g·cm⁻³) and soil moisture content (SMC) were estimated [29]. The texture was determined using the hydrometer method. The soil was assigned to a textural class according to the USDA textural triangle. Electrical conductivity (EC) and pH were measured in a 1:1 (soil:water) extract using Orion Star™ A222 conductivity portable meter. Soil organic matter (SOM) was estimated using the mass loss on ignition method by placing samples in a muffle furnace at 440°C overnight. Nitrogen percentage was determined using the micro-Kjeldahl method. Nutrients (P, K, Na, Ca, and Mg) were processed according to EPA 3050B method and extracts measured using inductively coupled plasma optical emission spectroscopy (ICP-OES). Means were analyzed at P < 0.05 significance level in two-way analyses of variance using the software statistical package JMP 14 [30].

#### 2.3. Flora Analysis

The heights and diameters of mesquite trees were measured in four randomly quadrates of 50 × 50 m. Canopy cover was estimated using a 100 m line intercept running along the middle of each quadrat [31]. The crown diameter of trees canoping the small quadrates of annual species was measured in two perpendicular directions. Annual species were measured in a four quadrate of 1 × 1 m established under the understory and the uncapped adjacent areas of four randomly selected mesquite trees. Within the quadrates, existing annual plants were tallied. Species coverage was assessed using the Daubenmire method plot [32]. The relative density and frequency of species were calculated [31]. Shannon-Wiener index of annual species biodiversity (H') was calculated [33].

### 3. Results and Discussion

#### 3.1. Soil Physicochemical Properties

The results of the study indicated that sand comprised 96.4% of soil composition, while clay and silt constituted 3.4% and 0.2%, respectively. Soil BD ranged from 0.92 to 1.55 g·cm⁻³. An increasing trend in BD with depth was detected in the understory and the uncapped adjacent areas. Significant differences in BD were observed between the understory of mesquite trees and the uncapped adjacent areas at a depth of 0–5 cm (Figure 3). The low BD of soil in the understory could be attributed to the deposition of aeolian materials in the uncapped areas. In this respect, our results are in contrast with Tiedemann and Klemmedson [10], who reported lower bulk density in the 0–4.5 cm soil depth under mesquite trees compared to the open areas in southern rangelands of Arizona.

Moisture content in the soil profile ranged from 3.41% to 5.26% in the understory compared to 3.10%–21.9% in the uncapped adjacent areas. No significant differences were observed in SMC among various depths of the soil profile in the understory and the uncapped adjacent areas, except for the 40–60 cm layer (Figure 4). The observed lower soil moisture in the 40–60 cm layer in the understory of mesquite trees could be attributed to water root uptake from the lower level of the soil profile. Similar results were reported by Schade et al. [34], as indicated that *P. velutina* could use up soil water.
Soil pH was moderately alkaline, ranging from 7.9 to 8.1. The maximum pH was 8.1 ± 0.03 in 0–5 cm depth in the uncanopied areas compared to 7.9 ± 0.04 in the 20–40 cm depth understory. No significant differences in pH were observed between understory and the uncanopied areas. Electrical conductivity ranged from 1.44 to 3.56 mS/cm. Likewise, no significant differences in EC were found beneath and beyond the canopies of mesquite trees (Table 1).

Significant differences existed in SOM in 0–5 cm and 5–20 cm depths between the understory and the uncanopied areas. The SOM was more than twice the amount in the first two topsoil layers than those of uncanopied adjacent areas. However, a decrease in SOM was noticeable from the topsoil downwards in both understory and the uncanopied adjacent areas. The low level of SOM in this study compared to other ecosystems could be attributed to variations in moisture, pH, vegetation cover, land management, and land-use history [35–37]. Some scholars reported that mesquite trees could produce up to 6.1 tons per hectare per year [38]. In our case, harsh climatic conditions and sparse vegetation cover were the main factors contributing to low SOM content.

Likewise, significant differences existed in N percentage between the understory and the uncanopied areas, down to a depth of 20 cm. Nitrogen was twice the amount in the 0–5 cm and 5–20 cm depths in the understory compared to uncanopied adjacent areas. Our results confirmed those of Tiedemann and Klemmedson [10], Menezes and Salcedo [11], El-Keblawy and Al-Rawai [16], Mosweu et al. [39], and Najafi and Jalili [24] in different regions of the world. Many authors reported high nitrogen levels underneath trees and attributed that to the accumulation of organic matter within the crown boundaries and the nitrogen-fixing ability of the plants [40, 41].

A similar trend was found for the phosphorus, where concentration was higher in the depths of 0–5 cm and 5–20 cm in the understory than the comparable depths of uncanopied adjacent areas. Equally, significant differences existed in Magnesium (Mg) between the understory of
mesquite trees and the uncanopied adjacent areas, starting from topsoil to 20–40 cm depth. The result is consistent with Tiedemann and Klemmedson [10], Menezes and Salcedo [11], El-Keblawy and Al-Rawai [16], and Mosweu et al. [39]. The concentration of K showed a decreasing trend with soil depth in the understory, but not significant, compared to the uncanopied adjacent areas. The maximum concentration of K was 190 ± 122 in 0 to 5 cm in the understory of mesquite trees. However, the minimum level of K was 50.6 ± 8.06 in 20 to 40 cm depth in uncanopied areas. The result attested to the findings of Tiedemann and Klemmedson [10] and Menezes and Salcedo [11]. The decrease in K suggests that trees of *P. juliflora* absorb K from deeper layers and accumulate it on the top of the soil profile.

No significant differences in the levels of Na and Ca were observed between the understory and the uncanopied areas. Furthermore, no clear trend in these nutrients was detected with soil depth. Comparable results were reported by El-Keblawy and Al-Rawai [16] in the UAE desert and Kahi et al. [42] in the rangelands of Kenya as well as Menezes and Salcedo [11] in northeastern Brazil. The high concentration of some nutrients in the topsoil of *P. juliflora* understory was attributed to its high nutrient demands that impoverish lower soil profile and release nutrients when leaves decay [43].

### 3.2. Flora Impact

The results of the study showed that mesquite tree heights and diameters averaged 7 ± 1.57 m and 20 ± 8 cm, respectively. Trees were of a shrubby multi-stemmed form (Figure 5). The number of stems ranged between 5 and 6. The crown of trees ranged from 3.8 m to 27.8 m in diameter, averaging 12.5 ± 6.8 m. Large openings (up to 20%) existed in old trees due to the dieback of branches. The density of mesquite trees was 21 ± 1.31 treesha⁻¹, while the canopy covers averaged 14.68%. Associated flora was of an ephemeral type with a total of seven identified species (Table 2). Some of them like *Aizoon canariense* L. and *Emex spinosa* (L.) Campd. are of considerable antioxidant activities [44]. Species richness (*n* = 6) was the same in the understory of mesquite trees and uncanopied adjacent areas. However, the density of
Table 1: Mean values and standard errors (n = 32) of soil chemical properties in the understory of *P. juliflora* trees and the uncanopied adjacent areas*.

| Depth (cm) | Area/soil properties | EC (mS/cm) | pH | N (%) | P (mg·L⁻¹) | K (mg·L⁻¹) | Na (mg·L⁻¹) | Ca (mg·L⁻¹) | Mg (mg·L⁻¹) | SOM (%) |
|------------|-----------------------|------------|----|--------|-------------|-------------|--------------|--------------|-------------|---------|
| 0–5        | Understory           | 2.43 (1.09)AB | 8.08 (0.06)AB | 0.24 (0.05)A | 805 (233)A | 190 (122)A | 63 (36.8)A | 345 (125)A | 77.6 (36.2)ABC | 1.47 (0.30)A |
|            | Uncanopied           | 1.77 (0.57)AB | 8.10 (0.03)A | 0.11 (0.01)B | 347 (42.2)BC | 59.5 (31.6)A | 89.1 (75.4)A | 303 (60.6)A | 35.8 (9.66)BC | 0.67 (0.07)B |
| 5–20       | Understory           | 3.56 (0.89)A | 7.98 (0.07)AB | 0.18 (0.04)A | 511 (55.1)B | 182 (54.3)A | 107 (36)A | 572 (156)A | 96 (25)AB | 0.74 (0.11)B |
|            | Uncanopied           | 1.93 (0.44)AB | 8.02 (0.03)AB | 0.07 (0.01)BC | 209 (33.3)C | 55.5 (18.2)A | 73.9 (40)A | 382 (117)A | 38.7 (5.79)BC | 0.31 (0.07)C |
| 20–40      | Understory           | 3.41 (0.63)AB | 7.9 (0.04)B | 0.10 (0.01)BC | 234 (40.3)C | 155 (31.1)A | 123 (39)A | 547 (126)A | 98.9 (22.5)A | 0.41 (0.07)BC |
|            | Uncanopied           | 1.44 (0.45)B | 8.1 (0.07)B | 0.05 (0.01)BC | 175 (27.8)C | 50.6 (8.06)A | 24.2 (14.1)A | 350 (169)A | 30.5 (3.61)C | 0.12 (0.02)C |
| 40–60      | Understory           | 2.52 (0.77)AB | 8.03 (0.11)AB | 0.04 (0.004)BC | 137 (33.2)C | 121 (22.2)A | 104 (45.1)A | 395 (120)A | 84.7 (20.3)ABC | 0.12 (0.02)C |
|            | Uncanopied           | 2.75 (0.66)AB | 7.96 (0.06)AB | 0.04 (0.01)C | 147 (19.2)C | 69.1 (14.9)A | 98.4 (63.8)A | 585 (135)A | 62.7 (19.9)ABC | 0.21 (0.03)C |

*levels not connected by the same letter are significantly different (P < 0.05) according to Student’s t-test.
ephemerals in the uncanopied areas was higher than the canopied by 18%. The presence of forbs in the understory of mesquite trees was attributed to light shade created by openings in the canopy of trees [42]. Tiedemann and Klemmedson [10] attributed abundance and good growth of grasses under mesquite crowns to improved soil conditions, resulting from the concentration of nutrients from the lower layers.

The Shannon-Weaver index of diversity was higher in the uncanopied areas compared to the understory, calculating 1.27 and 1.18, respectively. Species evenness (Shannon Equitability ($H/\ln N$)) index in the uncanopied areas was 70.7% compared to 65.6% in the understory. The results of this study were in line with El-Keblawy and Al-Rawai [16], who reported lower frequency, density, and diversity indices of native species underneath canopies of mesquite trees in the rangeland of UAE.

Finally, since its introduction into the country, mesquite widely spreads in the rangelands of Bahrain due to seeds dissemination by camels. Recently, mesquite was categorized as slightly invasive with low invasion risks [45]. Nonetheless, mesquite thrives in a harsh environment and provides shade for native flora and fauna. Therefore, mesquite offers valuable environmental services in desert ecosystems through halting desertification and encountering the climate change effects in desert countries like Bahrain.

4. Conclusion

This study presented the influence of mesquite as an invasive species on some physicochemical properties of sandy soils and annual plants in Bahrain. The study showed mixed-effects of mesquite trees on soil’s properties. No differences in the pH, EC, K, Na, and Ca were found between the understory and uncanopied adjacent areas. However, significant differences existed in soil organic matter, N, P, and Mg between the two categories in the upper 20 cm of the soil. Mesquite trees did not affect species richness; nevertheless, species diversity was higher in the uncanopied areas compared to the understory.

Based on the results of this study, it can be concluded that mesquite enriches upper soil layers with some nutrients and organic matter. Moreover, its adverse effect on annual plants in the arid environment where sandy soils prevail is minimal. Mesquite proved to be an invasive and highly competitive species in many ecosystems of the World. Nonetheless, it did not function as an invasive species in the low-resources sandy ecosystem of Bahrain. Mesquite tolerates drought and fixes nitrogen in the soil. It stabilizes sands and nurses some annual understory plants. Therefore, we recommend planting the species to reclaim similar sandy ecosystems in the arid environment. In the meantime, we believe that critical knowledge gaps still exist regarding the
effects of mesquite invasion in particular ecosystems. Further research could be conducted to value the socioeconomic and environmental benefits of mesquite in light of climate change and the threat of widespread drought and desertification.

Data Availability

Data are available upon request from the corresponding author.

Disclosure

Ahmed A. Salih was formerly affiliated with Natural Resources & Environment Department, Arabian Gulf University. Jameel A. Alkhuzai was formerly affiliated with the University of Bahrain.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this work.

Acknowledgments

This study was conducted within the framework of the research plan of the Department of Natural Resources and Environment, Arabian Gulf University.

References

[1] O. E. Sala, F. S. Chapin, J. J. Armesto et al., “Global biodiversity scenarios for the year 2100,” Science, vol. 287, no. 5459, pp. 1770–1774, 2000.
[2] D. Simberloff, J.-L. Martin, P. Genovesi et al., “Impacts of biological invasions: what's what and the way forward,” Trends in Ecology & Evolution, vol. 28, no. 1, pp. 58–66, 2013.
[3] M. A. Garcia-Berthou, “Invasive plants and animals species: threats to ecosystem services,” in Climate Vulnerability: Understanding and addressing threats to essential resources, pp. 51–59, Academic Press, Amsterdam, Netherland, 2013.
[4] R. T. Shackleton, D. C. Le Maitre, N. M. Pasiecznik, and D. M. Richardson, “Prosopis: a global assessment of the biogeography, benefits, impacts and management of one of the World’s worst woody invasive plant taxa,” AoB PLANTS, vol. 6, 2014.
[5] P. Felker and P. R. Clark, “Nitrogen fixation (acetylene reduction) and cross inoculation in 12 Prosopis (mesquite) species,” Plant and Soil, vol. 57, no. 2-3, pp. 177–186, 1980.
[6] P. Felker, “Uses of tree legumes in semiarid regions,” Economic Botany, vol. 35, no. 2, pp. 174–186, 1981.
[7] M. T. Oliveira, V. Matzek, C. Dias Medeiros, R. Rivas, H. M. Falcão, and M. G. Santos, “Stress tolerance and eco-physiological ability of an invader and a native species in a seasonally dry tropical forest,” PLoS One, vol. 9, no. 8, Article ID e105514, 2014.
[8] R. Ahmad and S. Ismail, “Use of Prosopis in Arab/Gulf states including possible cultivation with saline water in deserts,” in Prosopis: Semiarid Fuelwood and Forage Tree: Building Consensus for the Disenfranchised, P. Felker and J. Moss, Eds., Center for Semi-Arid Resources, Kingsville, TX, USA, 1996.
[9] H. A. Paulsen, “A comparison of surface soil properties under mesquite and perennial grass,” Ecology, vol. 34, no. 4, pp. 727–732, 1953.
[10] A. R. Tiedemann and J. O. Klemmedson, “Effect of mesquite on physical and chemical properties of the soil,” Journal of Range Management, vol. 26, no. 1, pp. 27–29, 1973.
[11] R. S. C. Menezes and I. H. Salcedo, “Influence of tree species on the herbaceous understory and soil chemical characteristics in a silvopastoral system in semi-arid northeastern Brazil,” Revista Brasileira de Ciência do Solo, vol. 23, no. 4, pp. 817–826, 1999.
[12] V. E. Vallejo, Z. Arbeli, W. Terán, N. Lorenz, R. P. Dick, and F. Roldan, “Effect of land management and Prosopis juliflora (Sw.) DC trees on soil microbial community and enzymatic activities in intensive silvopastoral systems of Colombia,” Agriculture, Ecosystems & Environment, vol. 150, pp. 139–148, 2012.
[13] M. Moradi, F. Imani, H. Najj, S. Moradi Behbahani, and M. Ahmadi, “Variation in soil carbon stock and nutrient content in sand dunes after afforestation by Prosopis juliflora in the Khorasan province (Iran),” iForest—Biogeosciences and Forestry, vol. 10, no. 3, pp. 585–589, 2017.
[14] J. D. Deans, O. Diagne, J. Nizinski et al., “Comparative growth, biomass production, nutrient use and soil amelioration by nitrogen-fixing tree species in semi-arid Senegal,” Forest Ecology and Management, vol. 176, no. 1–3, pp. 253–264, 2003.
[15] P. K. Basavaraja, S. D. Sharma, M. S. Badrinath, S. Sridhara, and G. R. Haroon, “Prosopis juliflora—an efficient tree species for reclamation of salt affected soils,” Karnataka Journal of Agricultural Sciences, vol. 20, no. 4, pp. 727–731, 2007.
[16] A. El-Kelawy and A. Al-Rawai, “Impacts of the invasive exotic Prosopis juliflora (Sw.) D.C. on the native flora and soils of the UAE,” Plant Ecology, vol. 190, no. 1, pp. 23–35, 2007.
[17] G. Singh and S. Shukla, “Effects of Prosopis juliflora (DC.) tree on under canopy resources, diversity, and productivity of herbaceous vegetation in Indian desert,” Arid Land Research and Management, vol. 26, no. 2, pp. 151–165, 2012.
[18] R. Kaur, W. L. Gonzales, L. D. Llambi et al., “Community impacts of Prosopis juliflora invasion: biogeographic and congeneric comparisons,” PloS One, vol. 7, no. 9, Article ID e49666, 2012.
[19] A. El-Kelawy and M. A. Abdelfatah, “Impacts of native and invasive exotic Prosopis congers on soil properties and associated flora in the arid United Arab Emirates,” Journal of Arid Environments, vol. 100-101, pp. 1–8, 2014.
[20] N. C. d. Souza, M. Tabarelli, C. A. da Silva et al., “The introduced tree Prosopis juliflora is a serious threat to native species of the Brazilian Caatinga vegetation,” Science of the Total Environment, vol. 481, pp. 108–113, 2014.
[21] C. B. Pandey, A. K. Singh, D. Saha et al., “Prosopis juliflora (Swartz) DC.: an invasive alien in community grazing lands and its control through utilization in the Indian Thar Desert,” Arid Land Research and Management, vol. 33, no. 4, pp. 427–448, 2019.
[22] A. Mukherjee, A. D. Velankar, and H. N. Kumara, “Invasive Prosopis juliflora replacing the native floral community over three decades: a case study of a World heritage site, Keoladeo national park, India,” Biodiversity and Conservation, vol. 26, no. 12, pp. 2839–2856, 2017.
[23] N. Naidu, J. Schmerbeck, and S. Gartner, “What influences the plant community composition on Delhi ridge? The role played by Prosopis juliflora and anthropogenic disturbances,” Tropical Ecology, vol. 58, no. 1, pp. 33–43, 2017.
[24] T. S. Najafi and A. Jalili, "Effects of Prosopis juliflora (SW.) D.C. on some physical and chemical soil properties," *Iranian Journal of Range and Desert Research*, vol. 19, no. 3, pp. 406–420, 2012.

[25] R. D. van Klinken, J. Graham, and L. K. Flack, "Population ecology of hybrid mesquite (Prosopis species) in western Australia: how does it differ from native range invasions and what are the implications for impacts and management?" *Biological Invasions*, vol. 8, no. 4, pp. 727–741, 2006.

[26] F. Bagnouls and H. Gaussen, "Les climats biologiques et leur classification," *Annales de Géographie*, vol. 66, no. 355, pp. 193–220, 1957.

[27] E. M. Bridges and C. P. Burnham, "Soils of the state of Bahrain," *Journal of Soil Science*, vol. 31, no. 4, pp. 689–707, 1980.

[28] D. Brunsden, J. C. Doornkamp, and D. K. C. Jones, "The Bahrain surface materials resources survey and its application to regional planning," *The Geographical Journal*, vol. 145, no. 1, pp. 1–35, 1979.

[29] G. Estefan, R. Sommer, and J. Ryan, "Methods of soil, plant, and water analysis," *A Manual for the West Asia and North Africa Region*, ICARDA, Beirut, Lebanon, 2013.

[30] J. Sall, M. L. Stephens, A. Lehman, and S. Loring, *JMP Start Statistics: A Guide to Statistics and Data Analysis Using JMP*, Sas Institute, Cary, NC, USA, 2017.

[31] D. Mueller-Dombois and H. Ellenberg, *Aims and Methods of Vegetation Ecology*, Wiley, Hoboken, NJ, USA, 1974.

[32] C. D. Bonham, D. E. Mergen, and S. Montoya, "Plant cover estimation: a contiguous Daubenmire frame," *Rangelands*, vol. 26, no. 1, pp. 17–22, 2004.

[33] C. E. Shannon and W. Weiner, *The Mathematical Theory of Communication*, p. 177, University of Illinois Press, Urbana, IL, USA, 1963.

[34] J. D. Schade, R. Sponseller, S. L. Collins, and A. Stiles, "The influence of Prosopis canopies on understory vegetation: effects of landscape position," *Journal of Vegetation Science*, vol. 14, no. 5, pp. 743–750, 2003.

[35] M. M. Pulleman, J. Bouma, E. A. Van Essen, and E. W. Meijles, "Soil organic matter content as a function of different land use history," *Soil Science Society of America Journal*, vol. 64, no. 2, pp. 689–693, 2000.

[36] M. Pulido-Fernández, S. Schnabel, J. F. Lavado-Contador, I. M. Miralles Mellado, and R. Ortega Pérez, "Soil organic matter of Iberian open woodland rangelands as influenced by vegetation cover and land management," *Catena*, vol. 109, pp. 13–24, 2013.

[37] T.-Y. Ma, X.-Y. Liu, S.-Q. Xu et al., "Levels and variations of soil organic carbon and total nitrogen among forests in a hotspot region of high nitrogen deposition," *Science of The Total Environment*, vol. 713, Article ID 136620, 2020.

[38] V. K. Garg and R. Sponseller, "Influence of fuelwood trees on sodic soils," *Canadian Journal of Forest Research*, vol. 22, no. 5, pp. 729–735, 1992.

[39] S. Mosweu, C. Munyati, and T. Kabanda, "Modification of soil properties by Prosopis L. in the Kalahari desert, south-western Botswana," *Open Journal of Ecology*, vol. 3, no. 2, pp. 145–150, 2013.

[40] P. J. Zinke, "The pattern of influence of individual forest trees on soil properties," *Ecology*, vol. 43, no. 1, pp. 130–133, 1962.

[41] H. B. Johnson and H. S. Mayeux, "Prosopis glandulosa and the nitrogen balance of rangelands: extent and occurrence of nodulation," *Oecologia*, vol. 84, no. 2, pp. 176–185, 1990.

[42] H. C. Kahi, R. K. Ngugi, S. M. Mureithi, and J. C. Ng’ethe, "The canopy effects of Prosopis juliflora (dc.) and Accacia tortilis (hayne) trees on herbaceous plants species and soil physico-chemical properties in Njemps flats, Kenya," *Tropical and Subtropical Agroecosystems*, vol. 10, no. 3, pp. 441–449, 2009.

[43] R. Sharma and K. M. M. Dakshini, "A comparative assessment of the ecological effects of Prosopis cineraria and P. juliflora on the soil of revegetated spaces," *Vegetatio*, vol. 96, no. 1, pp. 87–96, 1991.

[44] A. A. Al-Laith, J. Alkhuzaei, and A. Freije, "Assessment of antioxidant activities of three wild medicinal plants from Bahrain," *Arabian Journal of Chemistry*, vol. 12, no. 8, pp. 2365–2371, 2019.

[45] A. M. Sadeq, "Risk assessment and management of invasive alien plant species: a case study of Prosopis juliflora (sw.) D.C. In the kingdom of Bahrain," Doctoral Dissertation. Arabian Gulf University, Manama, Bahrain, In press.