

1-1-2020

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CHANG, HANNA; HAN, SEUNG HYUN; KIM, SEONGJUN; AN, JIAE; ALATALO, JUHA; and SON, YOWHAN (2020) "Interactions between topsoil properties and ecophysiological responses of mangroves(*Avicennia marina*) along the tidal gradient in an arid region in Qatar," *Turkish Journal of Agriculture and Forestry*. Vol. 44: No. 2, Article 2. <https://doi.org/10.3906/tar-1905-17>
Available at: <https://journals.tubitak.gov.tr/agriculture/vol44/iss2/2>

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Interactions between topsoil properties and ecophysiological responses of mangroves (*Avicennia marina*) along the tidal gradient in an arid region in Qatar

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Received: 07.05.2019 • Accepted/Published Online: 15.08.2019 • Final Version: 01.04.2020

Abstract: This study investigated the interactions between topsoil properties and ecophysiological responses of *Avicennia marina* along the tidal gradient in an arid region in Qatar. In February 2017, three plots were established, each at a distance of 0 m (D0), 50 m (D50), and 100 m (D100) from the inland boundary of a mangrove forest. Soil samples were collected at 0–10-cm depth in each plot to determine the chemical properties, and the density of seedlings, saplings, and trees was measured. Moreover, above- (AGB) and below-ground biomass (BGB) were calculated using an allometric equation for *A. marina* with the measured diameter at breast height in February 2017. As an indicator of salt stress, chlorophyll fluorescence parameters were measured in October 2017. Salinity (45.60 ppt) and exchangeable sodium percentage (ESP; 29.02%) at D100 were significantly highest. AGB was higher at D100 (41.44 Mg ha⁻¹) than at D0 (0 Mg ha⁻¹) and D50 (7.33 Mg ha⁻¹), and BGB was higher at D100 (44.91 Mg ha⁻¹) than only at D0 (0 Mg ha⁻¹). There was no significant difference in the density of seedlings, saplings, or trees or the chlorophyll fluorescence parameters among the plots. Salt stress was not induced despite the hypersalinity at this site, since *A. marina* growing in an arid climate can endure strong salinity. Soil pH was highest at D0, followed by at D50 and D100. Organic matter, total nitrogen, available phosphorus, and cation exchange capacity were significantly higher at D100 than at D0 and D50. Higher concentrations of nutrients on the seaward side might result from the tidal gradient and a large input of organic matter and low soil alkalinity.

Key words: *Avicennia marina*, biomass, mangrove forest, soil property, topsoil

1. Introduction

Mangroves are highly productive woody plants that typically grow between land and sea, where the soils are considerably heterogeneous because of the tides (Wang et al., 2011). Since mangroves grow under unique soil conditions, numerous studies have examined the relationship between soil environmental conditions and mangroves in intertidal zones (Krauss et al., 2008; Feller et al., 2010).

Interactions between soils and plants under the tidal gradient could affect soil salinity and nutrients in mangrove forests. Mangrove species could grow with salts through salt uptake exclusion by roots, salt accumulation in leaves, and salt excretion by the gland (Osborne and Berjak, 1997); however, excessive salinity can induce salt stress, which decreases the growth and physiological activities of mangroves (Naidoo et al., 2011). Photosynthetic pigment and electron transport activity could be decreased by salt accumulation in leaves, and then chlorophyll fluorescence

would be decreased under the salt stress (Sudhir and Murthy, 2004). Thus, chlorophyll fluorescence could be used as an indicator of salt stress (Biber, 2006). Meanwhile, salts could be accumulated in the rhizosphere by excluded salts through the roots of mangrove species, resulting in increased salinity (Passioura et al., 1992).

Nutrients in soils are generally poor in mangrove forests due to the low decomposition rate and low microbial activity (Alongi et al., 2005; Reef et al., 2010). Therefore, mangroves may respond sensitively to changes in nutrient concentration. Increasing nutrient contents in soils could stimulate mangrove growth (Feller et al., 2003) and the structure and composition of mangroves could be influenced by species-specific responses to changes in nutrient contents (Ukpong, 2000). Mangroves also could increase soil nutrients through litter input (Xiong et al., 2018), bacterial nitrogen fixation (Inoue et al., 2011), root exudates (Inoue et al., 2011), and sediment accretion (Kumara et al., 2010).

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Mangrove forests are distributed mainly in subtropical and tropical regions and are rarely found in arid regions, where they have to endure more extreme conditions due to the hot and dry climate. Since salinity is correlated positively with temperature and negatively with the amount of precipitation (Saravanakumar et al., 2009), soil salinity is likely to be higher in arid regions (Naidoo et al., 2011). In addition, mangrove forests in arid regions show a lack of nutrients because of the low input of decomposable organic matter and low precipitation (Alongi et al., 2005). The soils and mangroves would interact more sensitively in extreme environments in an arid climate. However, there are few studies on the relationship between soils and mangroves under unique environments in arid regions (Alongi, 2000, 2005).

The objective of the present study was to investigate the relationship between topsoil properties and ecophysiological responses of *Avicennia marina*, the predominant species in arid mangrove forests, at different distances from the coast in an arid region in Qatar. The interactions between soil and mangroves might occur mainly in the topsoil since the mangrove roots and litter are mostly distributed in the upper layer of soil (Otero et al., 2006). We firstly hypothesized that the soil salinity would increase toward the sea with the tidal gradient and the soil salinity near the sea would be extremely high due to the arid climate. The salt stress of *A. marina* would increase according to the changes in soil salinity in a form decreasing the chlorophyll fluorescence. Secondly, we hypothesized that the gradient of nutrients would be developed by the tide as well as by interactions between soils and mangroves, and the gradient of nutrients would

be related to the gradient of mangrove biomass sensitively due to low input of soil nutrient sources in an arid region.

2. Materials and methods

The study site was a natural mangrove forest in Al-Thakira (629 ha), Qatar (25.6973°N, 51.5506°E; Figure), where the only mangrove species was *A. marina* (Al-Khayat and Balakrishnan, 2014). There are six mangrove forests and no other forests in the interior of Qatar. The rainy season in this area is from October to May with a mean annual precipitation of 78.1 mm. The temperature ranges from 35 to 50 °C during summer and from 15 to 30 °C during winter. The maximum tidal range (the height difference between the high and low tides) is 1.99 m and the soil is classified as Solonetz (Abulfatih et al., 2002). In February 2017, plots were set along the tidal gradient, at distances of 0 m (D0), 50 m (D50), and 100 m (D100) from the inland boundary of the mangrove forest towards the sea (Figure). Three subplots were established 20-m apart within a plot (Figure) and the size of the subplot was 2 × 2 m², 3 × 3 m², and 4 × 4 m² at D0, D50, and D100 according to the size of *A. marina*, respectively. This natural mangrove forest has expanded landward (D0) from the sea (D100).

Soil samples were collected from three random points per subplot at 0–10-cm depth in February 2017. The samples were air-dried and sieved through a 2-mm mesh screen and were then analyzed for chemical properties. The pH was measured in 1:5 soil-to-distilled water and salinity was calculated by multiplying electrical conductivity (EC; 1:5 soil-to-distilled water) by 0.064. Total nitrogen (TN) was analyzed using an elemental analyzer (vario Macro, Elementar Analysensysteme GmbH, Germany),

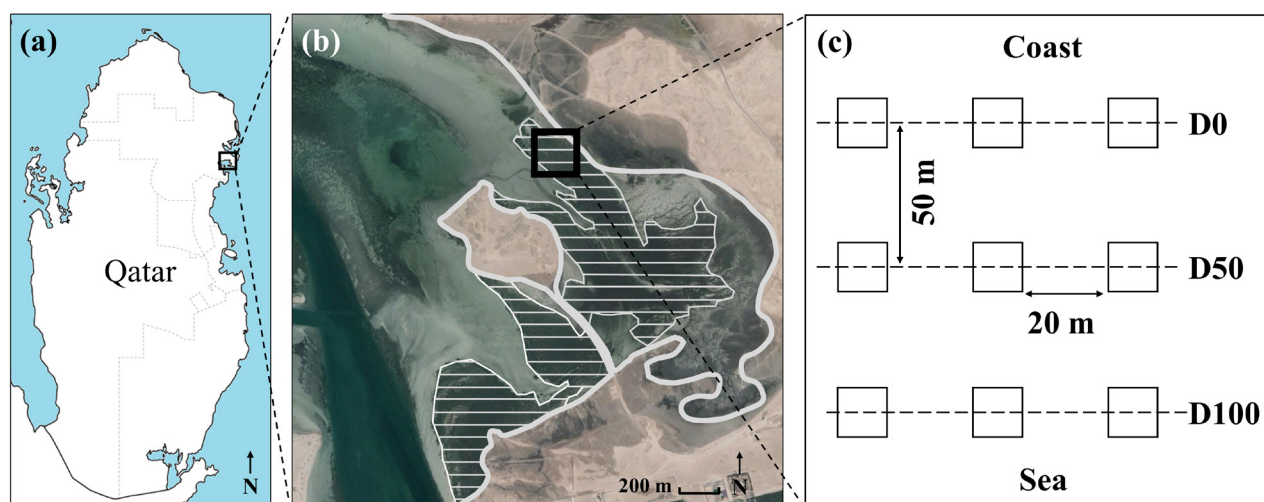


Figure. Location of the study site in Qatar (a, b) and plot design (c). The thick line indicates the coastal line and the hatched area indicates the mangrove forest in (b). Plots were located 0 m (D0), 50 m (D50), and 100 m (D100) from the inland boundary of the mangrove forest towards the sea.

and soil organic matter (OM) was measured using the method described by Walkley and Black (1934). Available phosphorus (P) and the concentrations of exchangeable cations (Ca²⁺, Mg²⁺, K⁺, and Na⁺) were determined in Mehlich 3 extracts with ICP-OES (730 series, Agilent Technologies Inc., USA). Extractable acidity was determined with the BaCl₂-triethanolamine method. Cation exchange capacity (CEC) was calculated as the sum of the concentrations of exchangeable cations and exchangeable acidity, and exchangeable sodium percentage (ESP) was calculated as the ratio of Na⁺ concentration to CEC.

Plant density was determined by counting the number of individual *A. marina* seedlings (≤50 cm height), saplings (≤1.3 m height), and trees (>1.3 m height) in each subplot. At D0, seedlings and saplings were found but no trees. The diameter at breast height (DBH) of all trees was measured in each subplot at D50 and D100. Above-ground biomass (AGB) and below-ground biomass (BGB) of trees were estimated using an allometric equation for *A. marina* (Eqs. (1) and (2); Comley and McGuinness, 2005).

$$\log(\text{AGB}) = -0.511 + 2.113 \log(\text{DBH}) \quad (1)$$

$$\log(\text{BGB}) = 0.106 + 1.171 \log(\text{DBH}) \quad (2)$$

Chlorophyll fluorescence was measured once at 08:00–10:00 AM in October 2017 because photosynthetic activity in *A. marina* is reduced during winter (December–February) (Hegazy, 1998). It was reported that the minimum fluorescence (Fo) would be increased and maximum fluorescence (Fm), maximum quantum yield of PS II (Fv/Fm), and performance index (PI_{abs}) would be decreased under salt stress. Thus, Fo, Fm, Fv/Fm, and PI_{abs} were measured in three randomly selected leaves of three trees in each subplot, using a Handy-PEA (Hansatech Instruments, UK) with 1500 μmol m⁻² s⁻¹ light after 30 min dark adaptation.

Differences in soil properties (pH, salinity, ESP, OM, TN, available P, and CEC), tree biomass, and chlorophyll fluorescence (Fo, Fm, Fv/Fm, and PI_{abs}) among the plots were analyzed using one-way ANOVA and Tukey's post

hoc test (n = 3). Differences in DBH between D50 and D100 were analyzed using a t-test (n = 3). All statistical analyses were performed using SAS 9.4 software (SAS Institute Inc., USA) and statistical significance was set at P < 0.05.

3. Results

Soil pH (mean ± standard error) was significantly highest at D0 (8.96 ± 0.03), followed by at D50 (8.78 ± 0.03) and D100 (8.51 ± 0.01) (Table 1). Salinity and ESP differed significantly between D100 and D0, and between D100 and D50. At D100, salinity of 45.60 ppt and ESP of 29.02% were recorded, which were 195% and 99% higher than those at D0, respectively, and 125% and 70% higher than those at D50, respectively (Table 1). OM at D100 was significantly 155% and 89% higher than that at D0 and D50, respectively (Table 1). Furthermore, there were significant differences in TN, available P, and CEC between D100 and D0 or D50; TN, available P, and CEC at D100 were 185%, 301%, and 23% higher compared to D0, respectively, and 115%, 237%, and 20% higher compared to D50, respectively (Table 1).

There was no significant difference in seedling, sapling, or tree density among the plots (Table 2). Seedling density at D0, D50, and D100 was 1.17 ± 0.22, 6.56 ± 3.07, and 1.50 ± 0.07 per m², and sapling density was 1.25 ± 0.14, 1.33 ± 0.80, and 0.35 ± 0.06 per m², respectively. Tree density was 0.9 ± 0.1 per m² at D50 and 1.2 ± 0.1 per m² at D100, and no trees were found at D0 (Table 2). The DBH of trees was significantly higher at D100 (2.98 cm) than at D50 (1.51 cm). AGB of trees was significantly higher at D100 (41.44 ± 9.73 Mg ha⁻¹) than at D0 (0 Mg ha⁻¹) and D50 (7.33 ± 4.93 Mg ha⁻¹). BGB of trees was higher at D100 (44.91 ± 3.16 Mg ha⁻¹) than at D0 (0 Mg ha⁻¹) and D50 (19.36 ± 12.00 Mg ha⁻¹), which was significant only between D100 and D0 (Table 3). Meanwhile, no significant differences in chlorophyll fluorescence were observed among the plots. The mean Fo, Fm, Fv/Fm, and PI_{abs} values among the plots were 233.24, 1044.20, 0.77, and 3.82, respectively (Table 4).

Table 1. Soil properties at 0 m (D0), 50 m (D50), and 100 m (D100) distance from the inland boundary of the mangrove (*Avicennia marina*) forest towards the sea at Al-Thakira, Qatar (n = 3). Values are presented as mean ± standard error and different letters indicate significant differences among plots.

Plot	pH	Salinity (ppt)	ESP (%)	OM (%)	TN (%)	Available P (mg kg ⁻¹)	CEC (cmol _c kg ⁻¹)
D0	8.96 ± 0.03 a	15.48 ± 0.55 b	14.58 ± 0.58 b	1.10 ± 0.06 b	0.05 ± 0.00 b	2.42 ± 0.10 b	134.82 ± 0.82 b
D50	8.78 ± 0.03 b	20.26 ± 0.96 b	17.04 ± 0.19 b	1.49 ± 0.06 b	0.07 ± 0.00 b	2.89 ± 0.10 b	138.44 ± 0.45 b
D100	8.51 ± 0.01 c	45.60 ± 5.36 a	29.02 ± 1.60 a	2.81 ± 0.16 a	0.15 ± 0.01 a	9.71 ± 2.24 a	165.94 ± 4.69 a

ESP: exchangeable sodium percentage; OM: organic matter; TN: total nitrogen concentration; Available P: available phosphorus; CEC: cation exchange capacity.

Table 2. Seedling, sapling, and tree density per m² at 0 m (D0), 50 m (D50), and 100 m (D100) distance from the inland boundary of the mangrove (*Avicennia marina*) forest towards the sea at Al-Thakira, Qatar (n = 3). Values are presented as mean ± standard error and there was no significant difference in density among plots.

Plot	Density (no. ha ⁻¹)		
	Seedling	Sapling	Tree
D0	11,666.67 ± 2204.79	12,500.00 ± 1443.38	0.00 ± 0.00
D50	65,555.56 ± 30,691.62	13,333.33 ± 8012.34	9259.26 ± 5185.19
D100	15,000.00 ± 721.69	3541.67 ± 551.20	11,666.67 ± 3410.56

Table 3. Above- and below-ground biomass (AGB and BGB) of *Avicennia marina* at 0 m (D0), 50 m (D50), and 100 m (D100) distance from the inland boundary of the mangrove (*Avicennia marina*) forest towards the sea at Al-Thakira, Qatar (n = 3). Values are presented as mean ± standard error and different letters indicate significant differences among plots.

Plot	AGB (Mg ha ⁻¹)	BGB (Mg ha ⁻¹)
D0	0.00 ± 0.00 b	0.00 ± 0.00 b
D50	7.33 ± 4.93 b	19.36 ± 12.00 ab
D100	41.44 ± 9.73 a	44.91 ± 3.16 a

4. Discussion

Salinity and ESP increased towards the sea since the soil near the sea is submerged by tidal seawater for a longer period than the soil near the inland boundary of the mangrove forest. Furthermore, the gradient of belowground biomass by the mangrove forest expansion from the seaward side might affect salt accumulation. It was reported that *A. marina* excluded sodium through its roots (Kramer and Preston, 1978; Reef and Lovelock, 2014) and, therefore, it could be accumulated in the rhizosphere (Passioura et al., 1992). In particular, the soil closest to the sea was hypersaline (45.60 ppt), showing higher salinity than seawater (about 35 ppt). This was related to the little precipitation and high evapotranspiration as a result of high temperature and light intensity in arid regions (Naidoo et al., 2011).

Despite the high salinity, no salt stress-induced inhibition was observed in the chlorophyll fluorescence or density of *A. marina* in contrast to hypothesis 1. In general, salt stress leads to an increase in Fo and a decrease in Fm, Fv/Fm, and PI_{abs} (Panda et al., 2006). However, the parameters of chlorophyll fluorescence were not affected by the hypersalinity in the current study, and they were within the respective ranges found in healthy leaves (Krause and Weis, 1991). Meanwhile, although mangroves

can endure extreme salinity, the mortality of *A. marina* increased under hypersaline soil (Dangremond et al., 2015). The density of seedlings, saplings, and trees was not significantly different along the tidal gradient, and *A. marina* could survive even in the hypersaline soil (45.6 ppt) in this study site. This might be related to the fact that *A. marina* could adapt to high salinity and dry conditions when it grows in arid regions (Khan and Aziz, 2001). In particular, it has a greater capacity for osmotic adjustment to salt accumulation (Khan and Aziz, 2001).

Nutrient variations in topsoils of mangrove forests are determined with seawater and other external sources such as precipitation and rivers (Wang et al., 2011). Soil nutrient contents might increase due to increased runoff after heavy rain (Castañeda-Moya et al., 2010) or due to induced large amounts of terrestrial runoff by rivers (Tam and Wong, 1998). However, since precipitation was considerably low due to the arid climate and there are no rivers in Qatar (Abulfatih et al., 2002), the soil nutrients are likely to depend on the tide at the site of the current study. Furthermore, TN and available P concentrations may be affected by the duration of inundation. The soil on the seaward side remained in anaerobic conditions for a longer period and thus received larger amounts of sulfate from seawater (Reef et al., 2010). Therefore, litter decomposition on the seaward side might occur mainly by anaerobic sulfate reduction, which stimulates the release of phosphorous and nitrogen fixation (Holguin et al., 2001).

Moreover, the gradient of the biomass of *A. marina* may affect the gradient of nutrients since there were low nutrient sources in the arid climate in accordance with hypothesis 2. According to the mangrove forest expansion from the seaward side, AGB and BGB of *A. marina* trees increased toward the sea in the present study. The OM also increased with tree biomass near the sea. This might be related to the increased input of leaves, branches, and roots by *A. marina* (Tam and Wong, 1998). It is known that the organic acids are produced during the process of

Table 4. Leaf chlorophyll fluorescence of *Avicennia marina* at 0 m (D0), 50 m (D50), and 100 m (D100) distance from the inland boundary of the mangrove (*Avicennia marina*) forest towards the sea at Al-Thakira, Qatar (n = 3). Values are presented as mean \pm standard error and there was no significant difference in chlorophyll fluorescence among plots.

Plot	Chlorophyll fluorescence			
	Fo	Fm	Fv/Fm	PI _{abs}
D0	243.44 \pm 7.38	1039.04 \pm 15.61	0.76 \pm 0.00	4.17 \pm 0.42
D50	229.63 \pm 6.88	1038.96 \pm 72.98	0.77 \pm 0.01	3.38 \pm 0.52
D100	226.65 \pm 9.32	1054.61 \pm 54.90	0.78 \pm 0.01	3.91 \pm 0.49

Fo: instantaneous chlorophyll fluorescence; Fm: maximum chlorophyll fluorescence; Fv/Fm: maximum quantum yield of PSII; PI_{abs}: performance index.

litter decomposition in the soil, and it could reduce soil pH (Tam and Wong, 1998). Soil pH decreased gradually as the distance from the inland boundary of the mangrove forest increased in the present study. Soil pH reduction due to organic acids may be greater on the seaward side due to high OM (Inoue et al., 2011). A large amount of OM and decreasing alkalinity might induce increasing amounts of nutrient sources (Lacerda et al., 1995) and nutrient availability in soils (Tam and Wong, 1998). Therefore, TN, available P, and CEC increased as the distance from the inland boundary of the mangrove forest increased.

In conclusion, this study aimed to investigate the interactions between topsoil properties and ecophysiological responses of *A. marina* along the tidal gradient in an arid mangrove forest. Substantial

differences in the responses of *A. marina* as well as the soil properties were observed along the tidal gradient. The soil salinity was affected by the gradient of the tide and belowground biomass of *A. marina*. However, salinity did not cause stress to *A. marina*, since *A. marina*, adapting to hot and dry conditions, could endure the hypersaline soil condition. The nutrient gradient likely depends on exposure to seawater and also on OM derived from *A. marina*.

Acknowledgments

This research was funded by a Qatar University Grant (QUUG-CAS-DBES-15/16-5), the Biodiversity Conservation Fund of Kazakhstan (Q1727701), and the Korean Ministry of Environment (2014001310008).

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