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CLASSIFICATION OF SOILS SUPPORTING MANGROVE PLANTATION IN KUWAIT

KLASSIFIZIERUNG VON BÖDEN MIT MANGROVE-PFLANZUNG IN KUWAIT

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The State of Kuwait has initiated an ambitious national program to establish greenery in 20 000 ha of open spaces in inland and coastal areas. Afforestation of intertidal zones with mangrove plants is being considered as a viable option for greening coastal areas. In view of this fact, experimental plantations were established using two ecotypes of *Avicennia marina* (Bahrain and UAE) and one ecotype of *Avicennia germinans* (Florida). The study consisted of two 10-year old plantations and two 2-year old plantations. Seedlings established successfully and grew vigorously on some of the locations within the site. Therefore, studies were conducted during 2002–2003 to describe and classify soils that supported maximum mangrove establishment and growth under the harsh arid coastal conditions of Kuwait. For this purpose, eight soil profiles (four each representing areas where seedlings established successfully and grew vigorously and where all seedlings died in the initial stages of establishment) were investigated and classified according to the soil taxonomy. The main soil types observed in the study site were: Typic Aquisalids, Typic/sodic Aquicambids and Calcic Aquisalids. Mangrove growth performance in relation to the landform, soil type and properties of the soil at various depths is discussed in the paper. The plant growth appeared to be the better on the typic Aquisalid soil than that on the Typic/sodic Aquicambid soils. The relative proportions of the coarse sand fraction, occurrence of the anaerobic layer in the profile and the surface layer salinity influenced both the establishment and growth of mangrove plants.

Keywords: Site selection; *Avicennia germinans*; *Avicennia marina*; Soil survey; Intertidal mudflats; Coastal greening

INTRODUCTION

Kuwait is located in the northeastern part of the Arabian Peninsula, between 28°33 and 30°05N latitudes and between 46°33 and 48°30E longitude. Its climate is arid with hot or very hot dry summers and cool to mild winters. The temperature range is large, with means during the warmest and coolest months ranging between 46.2°C and 6.9°C (Annual Statistical Abstract, 1998). Frost may occur in winter. Annual rainfall is low; about 120 mm. The mean annual rainfall is 115 mm, with great variability from year to year (28–260 mm) and from place to place. The rate of evaporation ranges from

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3.0 mm/day in January to 14.1 mm/day in July The relative humidity is generally low, and strong, dry and hot, northwesterly winds prevail during summer, particularly in June and July.

Kuwait has a 290 km long coastline, of which approximately 57% is the intertidal zone. This area is included in the national greenery plan that is currently being implemented by the State of Kuwait. Afforestation of intertidal zones with mangrove plants is considered a viable option to improve coastal environment and enrich marine biodiversity. Therefore, the Kuwait Institute for Scientific Research (KISR) initiated studies to introduce and naturalize mangrove species (*Avicennia marina, Avicennia germinans* and *Ceriops tagal*) to Kuwait's coastal conditions. For this purpose, the first experimental plantation of *Avicennia marina* was established in 1993 (Abu El-Nil *et al.*, 2001) and subsequently, five more have been established during 1999–2000 (Bhat *et al.*, 2002). Periodic observations indicated that the growth performance of different mangrove ecotypes varied considerably both from site to site and even within the same site. These observations clearly suggested that mangrove plantations can not be established on all soils under Kuwait's coastal environment.

Avicennia marina is a hardy mangrove species known for its tolerance to environmental stresses, particularly to temperature extremes and high salinity (Clough, 1993), although the growth of trees is influenced by a combination of stress factors (Al-Muharami, 1994). It thrives in a number of soils, often rooting into deep, water-saturated anaerobic layers. In Australia, mangroves grow in soils with a wide rage of soil textures, from coarse sand through fine alluvial soils, heavy clays and peats, but most soils have soil salinity near to that of the tidal water (Clough, 1993). In Andaman Nicobar Islands, they grow in acid sulphate, low pH soils classified according to soil taxonomy as halic sulfaquepts (Mongia *et al.*, 1993). A soil survey of the Qurm Nature Reserve in Oman established that *A. marina* trees while tolerant of a range of soil types, flourished in fine sandy loams of moderate salinity (Cookson *et al.*, 2002). The soil-seawater-plant interactions determine the growth and distribution of mangrove species in a given location (Ogino, 1993). Similarly, Kogo (1986) suggested low soil fertility to be a factor limiting mangrove growth in coastal Arabia. Unfortunately, although efforts are being made to introduce mangroves to Kuwait's coastline, information is lacking on the classification of soils that supports successful establishment and growth of mangroves. Therefore, the aim of the present study was to describe the soil profiles along Kuwait's coastline in relation to visual assessment of mangrove performance in order to first classify soils in accordance with the requirements of soil taxonomy, and secondly, to describe those characteristics most in common with good establishment and growth performance.

MATERIALS AND METHODS

Selection of experimental sites

In 1993, mangrove (*Avicennia marina* (Forssk) Vierh) plantations were established on two sites that were found suitable. However, the sites for the recent plantations were selected based on field surveys and soil analysis results. A recent aerial photograph and coastal environment data were used to initially identify potential sites along Kuwait's coastline (Al-Sarawi *et al.*, 1985). These sites were assessed for various parameters, such as accessibility; grazing pressure; texture of mudflats; topography;

tidal coverage; presence of household wastes, construction materials and rubbles; contamination by fresh oil spills; discharge of drainage effluents; and accumulation of salt crystals on the soil surface. The five sites that fulfilled most of these criteria were investigated further by studying multiple soil profiles and analysing representative soil samples from each site for a number of physical and chemical properties to select suitable area for planting.

Field planting

Acclimatized seedlings of *Avicennia marina* with an average height of 20–25 cm were planted in five selected sites. Thirty-cm planting holes were prepared in three or more rows (tidal line, one or more lines on either side of the tidal line at 1 × 1 m spacing (Figure 1a). The taproot with its root ball intact was inserted into the planting holes and back-filled with the native soil.

Assessment of seedling performance and soil properties

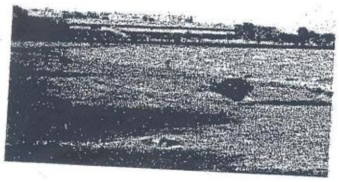
Survival and growth of seedlings at different locations within the new plantation site were monitored initially at 3-month intervals and then periodically. The sites that contained both old (10-year) and new (2-year) plantations of different mangrove ecotypes were used to describe and classify the soils that produced most vigorous plants under Kuwait's harsh environment.

Eight soil pits were dug at various locations at each plantation site, to just below the depth of standing water, during July-August 2003. Soil profiles (termed as 'pedons') and different horizons in each pedon were described using USDA (Soil Survey Division Staff, 1993) guidelines. A representative soil sample of approximately 1 kg was collected from each horizon for laboratory analysis. Soil samples were air-dried, crushed and passed through a 2-mm sieve to separate rock, gravel (2-mm or more in diameter) and fine fractions (< 2 mm diameter). The weight of each fraction was recorded and the gravel/rock fragments were discarded. Soil samples were stored in rigid polyethylene containers at room temperature before the laboratory analysis.

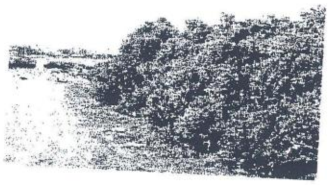
The fine soil fraction was analysed for a range of physical and chemical characteristics according to the recommended procedures (USDA, 1988, 1995, 1996; ③
⑤ Page *et al.*, 1982). Soil reaction (pH) was determined in the saturated paste and salinity determined using the electrical conductivity (EC) meter. $CaCO_3$ concentration in soil was determined using a calcimeter. $CaCO_3$ is expressed as percentages by weight. Sodium (Na^+) and potassium (K^+) concentrations in the extract were determined separately using a flame emission spectroscopy (Jenway FES) and calcium (Ca^{+2}) plus magnesium (Mg^{+2}) concentrations were measured by versenate titration with ethylene diamine tetra acetic acid (EDTA) in the presence of ammonium chloride ammonium hydroxide buffer solution and eriochrome black T indicator. The carbonates (CO_3^{-2}) and bicarbonate (HCO_3^-) were measured by titration with sulfuric acid, using phenolphthalein and methyl orange indicators, respectively. The chlorides measured by titration with silver nitrate using potassium chromate as indicator. The SO_4^{-2} was calculated by the difference between total measured anions
⑦ and $CO_3 + HCO_3 + Cl$ (Bresler *et al.*, 1982). Ionic concentrations are expressed as milliequivalents per liter of extract (meq l^{-1}).

(a). An overview of the field planted with mangrove seedlings.

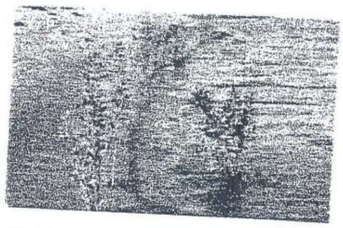
(b). Ten-year old Bahrain Ecotype of *Avicennia marina*.



(c). Poor establishment of seedlings in muddy sites below the tidal line.



(d). Ten-year old UAE Ecotype of *Avicennia marina*.



(e). Two-year old Florida Ecotype of *Avicennia germinans*.

(9) FIGURE 1 Comparison of location of seedlings and growth performance of various ecotypes of *Avicennia*. (a) An overview of the field planted with mangrove seedlings. (b) Ten-year old Bahrain Ecotype of *Avicennia marina*. (c) Poor establishment of seedlings in muddy sites below the tidal line. (d) Ten-year old UAE Ecotype of *Avicennia marina*. (e) Two-year old Florida Ecotype of *Avicennia germinans*.

The mean sodium adsorption Ratio (SAR) for each horizon was calculated for saturated soil paste extract using ionic concentrations expressed in meq l^{-1} as follows:

$$SAR = \frac{Na^+}{\{(Ca^{+2} + Mg^{+2})/2\}^{1/2}} \text{ in } (\text{mmoles/l})^{1/2}$$

Soil texture was determined by a modified hydrometer method supplemented with wet sieving (Shahid, 1992). For this purpose, the soils were dispersed with 4% sodium hexametaphosphate solution and the USDA textural class (USDA, 1993) was used to report soil texture, by plotting the sand (2–0.05 mm), silt (0.05–0.002 mm) and clay (< 0.002 mm) values on the textural triangle. Sand fraction was further separated into very coarse sand (1–2 mm), coarse sand (0.5–1.0 mm), medium sand (0.25–0.5 mm), fine sand (0.1–0.25 mm) and very fine sand (0.05–0.1 mm). Similarly, silt fraction was further separated as coarse silt (0.02–0.05 mm) and fine silt (0.002–0.02 mm). These soil fractions are expressed as a percentage of total fine (< 2 mm) fractions.

RESULTS AND DISCUSSION

Geomorphology of the study site

The study site is situated in the Kuwait Bay (Figure 2). The subsurface and surface geology of Kuwait are thought to be the result of interaction of the unstable Zagros Orogeny and the relatively stable Arabian Shield. Beach sediments along Kuwait's coast vary in size from silt and clay to large boulders found at the base of the cliffs. Generally carbonate sediments predominate in the south, while the land-derived clastics dominate in the north (Al-Sarawi *et al.*, 1985). The Pleistocene and Holocene Oolitic carbonate sediments along the southern coast belong to the northernmost marginal sector of the carbonate province of the shallow Arabian shelf, which extends from the Strait of Hormuz in the south up to the Tigris-Euphrates delta in the north (Picha, 1978). Embayments feature the coast in the study area.

The important parameters affecting marine environment are temperature, salinity, tides, currents and waves. Water temperature ranges between 13.2°C and 31.5°C, and

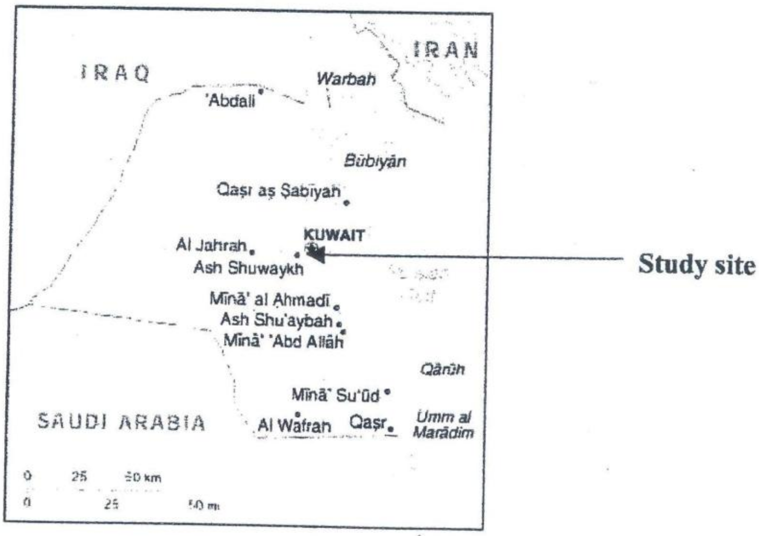


FIGURE 2 Kuwait map indicating the location of the study site.

salinity fluctuates between 38.6 and 42.4% (Subandar *et al.*, 2001). The tides in the Kuwait Bay are semidiurnal, ranging from 0.5 m (neap tides) to 4.2 m (spring tides) and run parallel to the coast. The maximum current velocity recorded during neap and spring tides never exceeded 50 cm s^{-1} (Abou-Seida and Al-Sarawi, 1990). The geomorphology of marine environment in Kuwait encourages the formation of highly sedimentary soft-substrate habitats (mudflats).

Classification and characterization of soils in mangrove plantation

In the Bahrain ecotype of *Avicennia marina*, the majority of the seedlings planted in the sandy area above the tidal line survived and produced spreading plants with luxuriant foliage and dense canopies (Figure 1b). In contrast, only a handful of the seedlings survived below the tidal line and grew poorly (Figure 1c).

The soil that produced the most vigorous plants in the Bahrain ecotype is classified according to soil taxonomy as Typic Aquisalids (Table I). The surface layer (Az) of this pedon comprised of granular non-sticky coarse to medium sand and had a strong effervescence reaction with dilute HCl. This layer was free of mottles and roots. The deeper layers (Bzg1 and Bzg2) had wavy boundaries and contained granular, non-sticky coarse to medium sand fractions and fine gravels. Unlike the surface layer, this layer contained medium-sized mottles and roots. In contrast, the soils in areas that were devoid of mangrove plants are classified as Typic/sodic Aquicambid (pedons 2 and 3). The pedons in these areas had clear, smooth or wavy boundaries and all were free of mottles. The soil was slightly effervescent reflecting the presence of relatively lower amounts of calcium carbonate. These are Aquisalids with salic horizons of 15 cm or more thickness and 1 : 1 EC greater than 30 dS m^{-1}. The soil in sites farther away from

TABLE I Classification, location and description of Pedon 1 in 10-year old Bahrain ecotype mangrove plantation

Parameter		*Description*
Classification		Typic Aquisalids, sandy-skeletal, mixed hyperthermic
Location		Shuwaikh
Physiographic position		One to three m above tidal line
Slope Class		Sloping
Slope		3%
Vegetation/Mangrove growth performance		Dense mangrove growth with low-growing spreading plants with luxuriant foliage and dense canopy. Spreading plants with an average height and width of 150–170 and 150 cm, respectively
Parent material		Alluvium
Depth to free water in profile		70 cm
Remark		High crab activity. Salt crystal deposition on the foliage.
Horizon	*Depth (cm)*	*Description*
Az	0–15	Pale yellow (5Y 7/3), granular, non-sticky, no roots, strong effervescence, coarse to medium sand, clear smooth boundary, few very fine pores, low excavation difficulty, no mottles, coarse gravels
Bzg1	15–40	Light gray (2.5Y 7/2), granular, non-sticky, few fine roots, strong effervescence, sandy, clear wavy boundary, common medium pores, low excavation difficulty, few medium sized mottles, gravels present
Bzg2	40–55	Light gray (2.5Y 7/2), granular, non-sticky, fine roots, strong effervescence, sandy, clear wavy boundary, many medium pores, low excavation difficulty, few medium sized mottles, fine gravels

⑧ TABLE II Classification, location and description of Pedon 2 in 10-year old Bahrain Ecotype mangrove plantation

Parameter		*Description*
Classification		Typic/sodic Aquicambids, sandy, mixed, hyperthermic
Location		Shuwaikh
Physiographic position		Above tidal line
Slope Class		Gently slopping
Slope		1–2%
Vegetation/mangrove Growth performance		No mangrove plants
Parent material		Alluvium
Depth to free water in profile		60 cm
Remark		Coarse gravels on surface
Horizon	*Depth (cm)*	*Description*
A	0–5	Light gray (2.5Y 7/2), granular, non-sticky, no roots, very slight effervescence, coarse to medium sand, clear smooth boundary, few very fine pores, low excavation difficulty, no mottles, coarse gravels present.
	5–10	Light gray (2.5Y 7/2), granular, non-sticky, no roots, very slight effervescence, medium sandy, clear smooth boundary, common medium pores, low excavation difficulty, no mottles, fine gravels present.
B2	10–40	Light gray (2.5Y 7/1), granular, non-sticky, no roots, very slight effervescence, coarse sandy, clear smooth boundary, many medium pores, low excavation difficulty, no mottles, no gravels.
B3	40 +	Light yellowish brown (2.5Y 6/3), granular, non-sticky, no roots, very slight effervescence, coarse sandy, clear smooth boundary, many very coarse pores, low excavation difficulty, no mottles, no gravels.

tidal line is Calcic Aquisalid or Typic Aquisalid and contained high proportions of fine sand, silt and clay in the surface and subsurface layers.

The seedlings of the Florida ecotype of *Avicennia germinans* transplanted along the tidal line established successfully and attained an average height of 70 cm in two years. In contrast, those planted either in the mudflat or outer sandy area did not survive. Although the soils at this site belonged to Typic Aquisalid group, they differed considerably in their textural composition (pedons 3–4 in Table IX). The soils in areas that produced maximum number of vigorous seedlings contained greater proportions of coarse to medium sand fractions than those where seedlings could not establish or grew poorly (Table IX). The surface layer at these locations had higher clay contents and fine mottles.

The seedlings of the UAE ecotype established successfully and attained an average height of 2.5 to 3.0 m in 10 years in mudflats about 1–2 m inside the tidal line (Plate 1c). The soil at this site is classified as the Typic Aquisalids (Table V). The upper 5 cm layer of this pedon contained granular, non-sticky coarse sand with little effervescence reaction and was free of mottles. The soil in the subsurface and deeper layers was granular, slightly sticky and contained medium-sized mottles. In contrast, the seedlings that were planted either above or below the tidal line did not survive. The soil at these sites, is classified as Calcic Aquisalids, was granular slightly sticky to sticky, contained very fine pores and had salt accumulation at the surface (Table VI). The soil contained coarse to medium sized mottles throughout the profile.

At the pedon 7 site, which is situated on the tidal line, 40% of seedlings survived and attained an average height of 100 cm in 2 years. The soil at this site, the Typic

(8) Table III Classification, location and description of Pedon 3 in 2-year old Florida Ecotype mangrove plantation

Parameter		*Description*
Classification		Typic Aquisalids, sandy, mixed, hyperthermic.
Location		Shuwaikh
Physiographic position		Along tidal line.
Slope Class		Almost level
Slope		< 1%
Vegetation/mangrove Growth performance		Good vegetative growth with average plant height of 70–80 cm.
Parent material		Alluvium
Depth to free water in profile		15 cm
Remark		Gravels observed below 30 cm.
Horizon	*Depth (cm)*	*Description*
Az	0–5	Light olive grey (5Y 6/2), granular, non-sticky, no roots, no effervescence, very coarse sandy, clear smooth boundary, few very fine pores, low excavation difficulty, no mottles, no gravels.
Bzg1	5–15	Olive grey (5Y 5/3), granular, non-sticky, no roots, slight effervescence, very coarse sandy, clear wavy boundary, common medium pores, low excavation difficulty, many medium-sized mottles, gravels.
Bzg2	15–30	Light brownish gray (2.5Y 6/2), granular, non-sticky, no roots, slight effervescence, very coarse sandy, clear smooth boundary, common medium pores, low excavation difficulty, many medium-sized mottles, gravels present.

(8) Table IV Classification, location and description of Pedon 4 in 2-year old Florida Ecotype mangrove plantation

Parameter		*Description*
Classification		Typic Aquisalids, coarse loamy, mixed, hyperthermic
Location		Shuwaikh
Physiographic position		Below tidal line
Slope class		Almost level
Slope		< 1%
Vegetation/mangrove Growth performance		Dead mangrove plants
Parent material		Alluvium
Depth to free water in profile		15 cm
Remarks		Rocks on surface and coarse fragments in all depths
Horizon	*Depth (cm)*	*Description*
Azg1	0–5	Light brownish grey (2.5Y 6/2), granular, slightly sticky, no roots, very slight effervescence, loamy sand, sand, gradual smooth boundary, few very fine pores, medium excavation difficulty, many medium mottles, few gravels.
Azg2	5–15	Light brownish grey (2.5Y 6/2), granular, slightly sticky, no roots, very slight effervescence, sandy, gradual wavy boundary, common medium pores, medium excavation difficulty, many medium-sized mottles, fine gravels present.
Bzg	15 +	Light grey (2.5Y 7/2), granular, granular, non-sticky, no roots, very slight effervescence, sandy, common medium pores, low excavation difficulty, many coarse mottles, no gravels.

Aquisalids, is granular, non-sticky to slightly sticky and contained fine mottles (Table VII). The presence of salic horizon with aridic soil moisture regime classifies it into Aridisols. These have salic horizon of at least 15 cm thickness and have an EC greater than 30 dS m^{-1} in 1.1 soil water extract for at least 90 consecutive days per year and

TABLE V Classification, location and description of Pedon 5 in 10-year-old UAE ecotype mangrove plantation

Parameter		*Description*
Classification		Typic Aquisalids, sandy, mixed, hyperthermic
Location		Shuwaikh
Physiographic position		One to two metres below tidal line.
Slope class		Almost level.
Slope		< 1%
Vegetation/mangrove Growth performance		Good Mangroves vegetation, dense, thick, bushy with average height of plants 250–300 cm. And 200 m width
Parent material		Alluvium
Depth to free water in profile		22 cm
Remark		Surface deposition of salts observed, increased crab activity, good number of pneumatophores observed for all plants
Horizon	*Depth (cm)*	*Description*
Az	0–5	Light grey (5Y 7/2), granular, granular, non-sticky, few coarse roots, very slight effervescence, sandy, clear wavy boundary, many fine pores, low excavation difficulty, no mottles, no gravels.
Bz1	5–15	Light olive grey (5Y 6/2), granular, granular, slightly sticky, few coarse roots, slight effervescence, loamy sand, clear smooth boundary, many fine pores, low excavation difficulty, no mottles, no gravels.
Bz2	15–25	Light olive grey (2.5Y 7/2), granular, non-sticky, no roots, very slight effervescence, sandy, many fine pores, low excavation difficulty, medium-sized mottles, no gravels

TABLE VI Classification, location and description of Pedon 6 in 10-year-old UAE ecotype mangrove plantation

Parameter		*Description*
Classification		Calcic Aquisalids, sandy, mixed, hyperthermic.
Location		Shuwaikh
Physiographic position		Along tidal line.
Slope class		Gently sloping.
Slope		1–3%
Vegetation/mangrove growth performance		Mangroves dead.
Parent material		Alluvium
Depth to free water in profile		10 cm
Remark		Salt accumulation at the surface, algal deposits on surface layers.
Horizon	*Depth (cm)*	*Description*
Akz	0–15	Light olive grey (5Y 6/2), granular, granular, slightly sticky, no roots, strong effervescence, sandy loam, clear wavy boundary, few very fine pores, low excavation difficulty, no mottles, no gravels.
Bkz1	5–15	Light olive grey (5Y 6/2), granular, granular, sticky, no roots, strong effervescence, sandy loam, abrupt wavy boundary, few very fine pores, medium excavation difficulty, a few fine mottles, no gravels.
Bkz2	15 +	Grey (5 Y 6/1), granular, slightly sticky, no roots, strong effervescence, loamy sand, a few very fine pores, high excavation difficulty, no mottles, no gravels.

a product of EC in dS m^{-1} and thickness in cm equal to 900 or more. As they have no special characteristics and are of common type, these are classified as Typic Aquisalids.

The soils at pedon 8 site are granular, sandy in the upper layer to clayey in the lower layers, slightly to strongly effervescent. Mottles were absent at all depths in the profile.

TABLE VII Classification, location and description of Pedon 7 in 2-year-old UAE ecotype mangrove plantation

Parameter	*Description*
Classification	Typic aquisalids, sandy, mixed, hyperthermic.
Location	Shuwaikh
Physiographic position	Below tidal line.
Slope class	Almost level.
Slope	1%
Vegetation/mangrove growth performance	Mangroves plants cover 25–30% area, average plant height is 100 cm.
Parent material	Alluvium
Depth to free water in profile	5 cm
Remarks	Algal deposition on surface, surface condition is muddy.

Horizon	*Depth (cm)*	*Description*
Az1	0–5	Light olive grey (5Y 6/2), granular, non-sticky, no roots, strong effervescence, loamy sand, clear wavy boundary, few very fine pores, low excavation difficulty, few fine mottles, no gravels.
Az2	5–10	Olive grey (5Y 5/2), granular, slightly sticky, no roots, strong effervescence, loamy sand, medium excavation difficulty, no mottles, no gravels.
Bz	10–30	Light olive grey (5Y 6/2), granular, non-sticky, no roots, slight effervescence, sandy loam, medium excavation difficulty, few fine mottles, no gravels.

(8) TABLE VIII Classification, location and description of Pedon 8 in 2-year-old UAE ecotype mangrove plantation

Parameter	*Description*
Classification	Typic Aquisalids, sandy, mixed, hyperthermic
Location	Shuwaikh
Physiographic position	One metre above tidal line
Slope class	Gently sloping
Slope	3%
Vegetation/mangrove growth performance	Mangroves dead
Parent material	Alluvium
Depth to free water in profile	15 cm
Remarks	Gravels, algal deposition and salt deposition seen on surface, surface condition is silty clay.

Horizon	*Depth (cm)*	*Description*
Az	0–5	Pale yellow (5Y 7/3), granular, non-sticky, no roots, slight effervescence, sandy, clear wavy boundary, few fine pores, low excavation difficulty, no mottles, fine gravels.
Bz1	5–15	Pale yellow (5Y 7/3), granular, slightly sticky, no roots, slight effervescence, sandy, diffuse wavy boundary, few medium pores, medium excavation difficulty, no mottles, no gravels
Bz2	15–30	Light olive grey (5Y 6/2), granular, sticky, no roots, strong effervescence, clayey, high excavation difficulty, no mottles, no gravels.

These soils are slightly to moderately alkaline and strongly saline. These are Typic Aquisalids, as they have no special characteristics to qualify into other groups and are of common type.

TABLE IX Particle-size analysis of soils from various pedons in the mangrove plantations

Pedon No. Ecotype	Plant Condition	Depth (cm)	Sand (%)						Silt (%)			Clay (%)	Textural class
			Total	Very Coarse	Coarse	Medium	Fine	Very fine	Total	Coarse	Fine		
1/Bahrain (old)	Healthy	0–10	93.2	5.8	30.4	51.0	5.8	0.2	2.6	0.2	2.4	4.2	Sand
	Vigorous	15–40	93.6	16.6	36.8	33.2	6.4	0.6	1.4	0.2	1.2	5.0	Sand
	Dense	40–55	93.2	19.0	32.0	33.0	8.2	1.0	2.2	0.4	1.8	4.6	Sand
2/Bahrain (old)	None	0–5	94	17.2	32.0	37.4	6.2	1.2	3.0	0.2	2.8	3.0	Sand
		5–10	96.8	5.0	24.6	54.4	10.8	2.0	0.2	0.1	0.1	3.0	Sand
		10–40	95.7	20.2	38.4	30.8	5.6	0.7	1.0	0.1	0.9	3.3	Sand
		40 +	97.6	18.5	43.0	31.8	3.2	0.1	0.4	0.0	0.4	2.0	Sand
3/Florida (new)	Healthy	0–5	97.4	80.8	9.6	3.8	2.6	0.6	0.8	0.2	0.6	1.8	Sand
	Vigorous	5–15	89.8	60.8	12.6	8.0	7.6	0.8	5.4	0.2	5.2	4.8	Sand
		15–30	93.8	64.2	15.8	8.0	5.6	0.2	3.6	0.0	3.6	2.6	Sand
4/Florida (new)	None	0–5	82.2	18.0	23.2	26.2	12.0	2.8	5.0	0.6	4.4	12.8	Loamy sand
		5–15	90.3	40.6	10.6	19.8	15.0	4.3	3.0	0.5	2.5	6.7	Sand
		15 +	92.5	29.2	21.6	23.0	14.6	4.1	1.0	0.8	0.2	6.5	Sand
5/UAE (old)	Healthy	0–5	92.4	12.4	25.4	32.8	20.6	1.2	3.0	0.4	2.6	4.6	Sand
	Vigorous	5–15	87.3	13.6	26.2	28.6	17.2	1.7	6.0	0.6	5.4	6.7	Loamy sand
	Tall, Dense	15–25	95.7	8.6	27.0	44.8	14.4	0.9	1.4	0.3	1.1	2.9	Sand
6/UAE (old)	None	0–5	81.8	4.4	15.8	23.2	35.8	2.6	6.0	0.6	5.4	12.2	Sandy loam
		5–15	68.5	1.2	14.8	41.0	10.2	1.3	19.0	0.5	18.5	12.5	Sandy loam
		15 +	84.8	10.8	24.4	31.4	17.0	1.2	8.4	0.3	8.1	6.8	Loamy sand
7/UAE (new)	Healthy	0–5	81.8	0.8	4.0	31.2	42.0	3.8	8.0	0.8	7.2	10.2	Loamy sand
	Vigorous	5–10	81.0	2.4	6.4	35.0	33.8	3.4	8.4	0.7	7.7	10.6	Loamy sand
		10–30	78.6	4.2	23.4	24.6	23.2	3.2	7.0	0.9	6.1	14.4	Sandy loam
8/ UAE (new)	None	0–5	96.64	12.0	26.4	47.0	11.0	0.2	0.4	0.1	0.3	3.0	Sand
		5–15	96.88	12.2	19.0	48.0	17.2	0.5	1.6	0.2	1.4	1.5	Sand
		15–30	38.28	3.2	11.0	12.6	10.0	1.5	21.0	1.0	20.0	40.7	Clay

Soil colour

Soil colour is probably a reliable indicator of the aerobic or anaerobic condition of the soil. The soils at sites that produced maximum number of vigorous seedlings have matrix hues of 5Y in the aerobic surface horizon, which change at varying depths to 2.5Y in strongly anaerobic range. The depth at which the hues change is related to landform and textural composition. In pedons 1, 3 and 5, which represented the most vigorous plants, the change in matrix hue occurred at 15 cm. In contrast, matrix hues did not change with increasing depth in pedons in sites that were devoid of mangroves (2, 4 and 6). While the soil color in pedons 2 and 4 was light gray (2.5Y 7/2) to light brownish gray (2.5Y 6/2), it was light olive gray in pedon 6. The pedon 7, which produced a fewer healthy plants, had matrix hue in the aerobic range (5Y).

Mottling was observed in horizons either directly above or in the anaerobic layer. These are usually associated with rooting pattern of mangrove types. In pedons situated in areas with vigorous mangrove plants, medium-sized mottles appeared at 5 (pedon 3) to 15 cm (pedons 1 and 5) depths. In contrast, the soils in areas without mangrove plants were either devoid of mottles at all depths (pedons 2, 6 and 8) or contained mottles in the surface layer (pedons 4).

Soil texture

The texture of soils in the experimental area is either sandy (pedons 1–5 and 8), sandy loam (pedon 6) or loamy sand (pedon 7). Although the total sand content in all pedons except for pedon 10 (15–30 cm layer contained 38.28% sand) is relatively uniform with depth, the proportion of individual sand fractions varied considerably in these profiles. The soils at all depths in pedons 1 to 4 contained greater proportions of very coarse to medium coarse sands compared to that in others. While the coarser sand fractions were uniformly higher at all depths in pedons 1 and 2, the surface soils (0–10 cm) in pedons 3 and 5 (both situated in areas with vigorously growing mangrove plants) contained higher amounts of these fractions. Pedons in sites where plants either died or grew poorly (pedons 2, 4, 6) had low coarse sand and high clay contents (6.5 to 40.72% in pedons 4, 6, 7 and 8) at all depths. These soils also had fewer pores than others.

It appears that the tidal flow of water, which constantly moves and mixes the soil has produced profiles with relatively uniform textures down stream but had less effect further upstream. As a consequence, in upstream locations, the alluvial gravel carried by water had been retained in place after deposition.

Soil chemical analysis

There was no uniform pattern in soil reaction in different soil horizons (Table X). In contrast, the salinity of soils exceeded 30 dS m^{-1}, with few exceptions (all depths in pedons 2 and 3; 0–10 cm layer in pedon 1; 0–5 cm layer in pedon 4 and 0–15 cm depth in pedon 8). In general, the subsurface layers had relatively higher salinity than the surface layers. The higher salinity levels recorded in sites under UAE ecotype suggest that this ecotype probably has a higher threshold levels for salinity than other types. The presence of high coarse sand fractions in pedon 2 appeared to have lowered the salinity of soils.

TABLE X Chemical analysis of soils from various pedons in mangrove plantation

Pedon No.	Horizon	Depth cm	pH	EC mS/cm	C %	N %	C:N	$CaCO_3$ %	Ca meq/l	Mg meq/l	Na meq/l	K meq/l	SAR	ESP	Cl meq/l	HCO_3 meq/l
Bahrain Ecotype (Old)																
1	A	0–5	7.8	29.0	0.050	0.080	0.63	9.78	14.0	42.5	301.4	6.3	57.75	46.42	320.0	2.00
	Bz1	15–0	7.7	48.9	0.073	0.073	1.00	11.95	22.5	83.5	579.7	11.2	79.63	54.43	490.0	2.00
	Bz2	40–5	7.8	46.3	0.066	0.080	0.85	10.72	23.0	77.0	579.7	9.9	81.98	55.15	625.0	1.00
2	A	0–	7.7	16.2	0.011	0.015	0.78	7.12	6.5	24.0	144.9	3.6	37.11	35.76	153.0	2.25
	B1	5–0	8.1	15.1	0.010	0.015	0.76	5.81	6.5	21.0	139.1	3.1	37.52	36.01	135.0	1.75
	B2	10–0	8.2	12.1	0.012	0.007	1.70	5.60	5.0	17.5	115.9	2.6	34.57	34.15	116.5	2.00
	B3	40 +	8.1	15.6	0.008	0.488	0.02	4.98	7.0	23.3	136.8	2.8	35.15	34.52	136.0	1.00
Florida Ecotype																
3	A	0–	7.6	27.0	0.114	0.109	1.05	4.62	13.5	52.5	359.4	6.0	62.57	48.41	300.0	4.50
	Bz1	5–5	7.4	42.8	0.129	0.134	0.96	7.17	32.5	84.5	492.8	10.0	64.42	49.14	515.0	3.50
	Bz2	15–0	7.6	40.1	0.082	0.149	0.55	6.30	28.5	70.5	475.4	9.4	67.57	50.33	517.5	3.00
4	Az	0–	7.8	47.8	0.123	0.225	0.55	7.63	26.0	89.5	608.7	9.5	80.10	54.58	491.0	3.50
	Bz1	5–5	7.7	52.0	0.059	0.051	1.15	5.71	25.0	98.0	637.7	9.6	81.31	54.95	554.0	1.50
	Bz2	15 +	8	43.0	0.061	0.076	0.81	5.77	21.0	73.0	550.7	8.2	80.33	54.65	457.0	1.50
UAE Ecotype (Old)																
5	A	0–	7.6	54.3	0.16	0.427	0.04	6.56	26.5	106.0	608.7	12.4	74.78	52.87	583.0	6.50
	Bz1	5–15	7.5	51.3	0.028	0.423	0.07	11.12	32.5	122.0	579.7	12.8	65.96	49.73	547.0	3.50
	Bz2	15–25	7.9	39.6	0.013	0.252	0.05	4.93	18.0	71.5	463.8	8.1	69.33	50.98	401.5	1.50
6	Akz	0–5	7.4	87.7	0.058	0.518	0.11	16.36	58.5	204.5	1072.5	21.8	93.52	58.38	986.5	12.50
	Bkz1	5–15	7.9	45.1	0.058	0.387	0.15	18.19	31.0	111.0	608.7	13.1	72.24	52.01	468.5	1.50
	Bkz2	15 +	7.9	35.5	0.052	0.171	0.30	12.70	23.0	94.0	394.2	10.6	51.54	43.6	382.0	1.00
UAE Ecotype (New)																
7	Az1	0–5	7.4	70.7	0.047	0.175	0.27	6.56	44.0	166.0	701.4	22.4	68.45	50.66	807.0	8.00
	Az2	5–10	7.7	57.5	0.071	0.219	0.33	11.12	42.5	120.0	695.7	16.2	77.18	53.65	612.0	2.75
8	Bz	10–30	7.9	59.8	0.082	0.135	0.61	4.93	36.0	123.5	695.7	17.8	77.90	53.88	655.0	3.00
	Az	0–5	7.9	24.2	0.032	0.171	0.19	5.22	11.5	39.5	224.9	5.6	44.54	40.05	230.5	2.50
	Bz1	5–15	8.1	26.9	0.041	0.241	0.17	5.78	15.5	44.5	313.0	6.8	57.15	46.16	263.5	1.00
	Bz2	15–30	7.6	50.4	0.096	0.941	0.10	21.62	23.0	96.0	608.7	14.0	78.91	54.21	533.0	2.50

ECe = Electrolyte conductivity

Sodium concentrations in soil extracts varied between 115.9 and 1072 meq l^{-1} (Table X). Chloride ion concentrations in extracts ranged between 116 to 986.5 meq l^{-1}. Soils were free from carbonates and gypsum, but contained 0.5 to 12.5 meq l^{-1} of bicarbonates and 1.77 to 21.62 % $CaCO_3$ (Table X). Additionally, soils contained 39.5 to 204 meq l^{-1} of Mg^{+2}, 5.0 to 58.5 meq l^{-1} of Ca^{+2} and 2.6 to 21.8 meq l^{-1} of K^+. The soils in the study area had low organic carbon and nitrogen contents. Kogo (1986) also suspected low soil fertility to be a main cause for poor performance of mangrove plants in Oman.

High sodium adsorption ratios (between 34.6 and 81.3%) and exchangeable sodium percentages (between 34.2 and 58.4%) in saturated soil paste extracts indicate strong sodic conditions.

Soil classification

In the most recent changes in the keys to soil taxonomy (USDA, 1994), a salic horizon now requires the following conditions: the thickness of at least 15 cm; an electrical conductivity (EC) greater than 30 dS m^{-1} in a 1 : 1 soil : water extract for at least 90 consecutive days per year, and a product of EC in dS m^{-1} and thickness in cm equal to 900 or more. The central concept of a salic horizon is one in which salts have accumulated in substantial amounts mainly through capillary rise of salt-saturated water from subsurface horizon in response to high rates of evaporation of water from the soil surface, followed by subsequent salt precipitation (USDA, 1994). Such a mechanism was probably responsible for the presence of high salt contents in mudflats. Furthermore, these sites are not regularly flushed by freshwater discharges. Therefore, the EC (1 : 1) of soils in most pedons exceeded 30 dS m^{-1} at all depths. It appears that although the soils at all depths in pedons 2 and 3, and the surface layer in pedons 1, 4 and 10 are reasonably saline, salt accumulation did not occur. This finding is similar to those of Dagar *et al.* (1993) and Cookson *et al.* 2002, in which soils under mangrove plantations in Bay Islands and Sultan Qaboos Qurm Nature Reserve (Oman) were found not to accumulate salts.

The soils having salic horizon with aridic soil temperature regime classify it into suborder salids. Salids that are saturated with water in one or more layers within 100 cm of the mineral surface for one month or more per year in six or more out of 10 years classify them into Aquisalids. These are Typic Aquisalids, as they have no special characteristics to qualify into other groups. The Aquisalids that have a Calcic horizon that has its upper boundary with 100 cm of soil surface classify it into Calcic Aquisalids.

The soils having ochric epipedon underlain by cambic horizon and aquic condition for sometimes in most years in one or more layer within 100 cm of soil surface classify them into Aquicambids. Aquicambids which have a horizon at least 25 cm thick within 100 cm of the soil surface that have an ESP of 15 or more (or SAR of 13 or more) during at least 1 month of the year in six or more years out of 10 qualify this as sodic Aquicambids.

Comparison of soil types with mangrove performance

The performance of mangrove ecotypes was determined on the basis of seedling establishment, average height and foliage density (Table XI). In the Bahrain ecotype, tallest plants showing luxuriant foliage and dense canopy were produced on the Typic

TABLE XI Key to landform, soil type and mangrove growth

ı	Dominant soil type	Particle-size class	Plant performance
	Typic Aquisalid	Sandy throughout	Good growth, over full coverage, luxuriant foliage and dense canopy
ɜar	Typic/sodic Aquicambid	Sandy throughout	None
ıg the	Typic Aquisalid	Sandy throughout	Good growth, luxuriant foliage, above 80% coverage, average height 70 cm
le the	Typic Aquisalid	Loamy sand surface and sandy subsurface layer	None
le the	Typic Aquisalid	Sandy surface/ loamy-sand to sand subsurface	Vigorous growth, 2.5 to 3.0 m tall, above 90% coverage, luxuriant foliage and growth
le the	Calcic Aquisalid	Sandy-loam/ loamy-sand clay content	None
side	Typic Aquisalid	Loamy sand, high clay content	25–30% coverage, healthy, coverage
:al	Typic Aquisalid	Sandy surface/clay subsurface	None

he tidal line. Seedlings failed to establish on the Typic/sodic
ɜ UAE and Florida ecotypes, most vigorous plants with luxuriant
ɜd in Typic Aquisalids.

a are Typic Aquisalids, as they have no special characteristics to
›ups. At some places they have a Calcic horizon to classify them
ls. At some locations they have ochric epipedon underlain by
quic condition persists for sometimes in most years in one or more
f soil surface. Such soils are classified as Aquicambids.
and contents and low silt and clay fractions. This condition along
ater table appears to have prevented excessive salt accumulation
tidal line. In contrast, the presence of silt and clay and water
›rizons in the mudflats are probably responsible for increased
ɜ places.

›sition, salinity of the surface layer and the occurrence of
ared to have played a major role in determining the
wth of mangrove plants. The occurrence of aerobic surface
›surface layer supported maximum seedling establishment and
l ecotypes. The Bahrain ecotype performed better in the
the surface horizon contained greater proportions of very

m^{-1}. In contrast,
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coarse to medium coarse sand and soil salinity lower than 30 dS m^{-1}. In contrast, sites that produced the most vigorous plants with luxuriant foliage in the UAE ecotype were situated below the tidal line and had soil salinity levels in excess of 30 dS m^{-1}. Excessive salt accumulation in the surface soil and/or high clay contents adversely affected plant performance in this ecotype. The Florida ecotype established better and grew faster in sites that are situated along the tidal line and contained greater proportions of coarse sand fractions and soil salinity of less than 30 dS m^{-1}. Relatively slow growth of mangroves in Kuwait is probably related to low soil fertility in the intertidal zone.

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