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A Comprehensive Analysis of Mangrove Soil in Eastern Lagoon National Park of Abu Dhabi Emirate

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Abstract

This paper presents comprehensive scientific details about mangrove soil in Eastern Lagoon National Park. A total of 36 sites were studied. From each site, two soil samples were collected for detailed characterization. The results indicate that mangrove soil is fine in texture at surface and coarser at subsurface. Soil salinity exceeds seawater salinity. pHs is dominantly in the neutral range. Soil salinity and sodicity are high due to high Na of the seawater. The high $CaCO_3$ *content sin the sediments are due to broken shells. The rich organic matter content is due to fall of mangrove leaves and decomposition. The total N is high compared to the available P. The high available K can be attributed to organic-rich mud. Furthermore, the hypothesis of similar soil characteristics across the study area is tested. The evaluation confirmed the hypothesis. Thus, a management strategy of mangroves is required for the entire study area.*

Keywords: Mangroves, soil physical properties, chemical properties, fertility status, organic matter content.

Introduction

Mangroves forestation in Abu Dhabi Emirate constitutes an important ecosystem. Abu Dhabi Emirate hosts approximately 110 km^2 of both natural and planted mangroves spread along 547 kilometers of shoreline, which provide a rich natural habitat and safe breeding ground for several animal species. Only one species of mangrove, *Avicennia marina* (Forssk.) Vierh. occurs in the Gulf region, other species, *Rhizophora mucronate Lam.* disappeared in historical times (Alsumaiti et al., 2017).

Abu Dhabi Emirate is consistently making efforts to increase mangrove plantation. Recently the Environment Agency of Abu Dhabi (EAD) partnered with the Tourism Development and Investment Company (TDIC) to plant 750,000 saplings of mangroves on 25% of the Saadiyat Island, which is currently being developed as a cultural hub of Abu Dhabi. The move is aimed at mitigating the environmental damages caused by the massive development on the island. Property developers are also urged to protect this endangered natural treasure by giving the environment proper consideration from the early planning stages of their development. Evaluating the spatial distribution and the areal extent of mangrove forests has been a research priority in the UAE due to the significant reduction in the forest area because of human and natural disturbances (Alsumaiti et al., 2017). Environmental factors including geomorphology, tidal range, and climate conditions tend to influence mangrove forests' productivity and distribution; some types of mangrove trees are more tolerant than others to variations in these environmental factors (Tam & Wong, 1998; English et al., 1997; Cintron et al., 1985). Notably, soil properties are one of the most important environmental factors that have a direct influence on mangrove structure, productivity, and distribution. Several researchers have examined the link between mangroves structure and various soil conditions. They found that the variations in trees' height and productivity are due to the temporal and spatial variation of soil properties such as soil salinity, soil nutrient availability, and soil fertility (Feller et al., 2002; McKee, 1993). Therefore, it is salient to comprehend the soils' physical and chemical characteristics from mangrove plantation to evaluate vegetation structure (Boto & Wellington, 1984).

In the last few years, researchers have conducted extensive studies regarding UAE inland soils (Shahid et al., 2014; Abdelfattah & Shahid, 2007; 2006). However, there is a lack of detailed research of the mangrove soils with an impetus to assess or explore mangrove forests' distribution and status. Data about soil properties and characteristics such as soil fertility can help in planning the best action of governing the ideal ecosystem and enhancing the soil quality. Scientifically, as a medium of growth, soil requires supplying sufficient nutrients and possessing good characteristics to increase the performance of a tree and in turn establish better forest ecology for wildlife while at the same time balancing the environmental condition (Rambok et al., 2010).

The main objective of the present work is to understand the key characteristics of soils in Eastern Lagoon Mangrove National Park in Abu Dhabi, UAE, and to evaluate the spatial variability of soil properties. This is achievable through testing the physical and chemical properties, fertility (nutrient) status, and organic matter contents. Another objective of this work is to create soil properties maps, using inverse distance weighted (IDW) interpolation in ArcGIS software, specific to the area of study. These maps show the spatial variation of soil characteristics at different sites and depths. In addition to the spatial variation of soil properties, the following hypothesis was also tested.

Hypothesis to be Tested

The Eastern Lagoon National Mangrove Park presents one soil type with minimal differences in soil properties (within standard deviation). If this hypothesis is supported, then the same management can be applied for the entire Park. If, however, different soil properties are found and demonstrate strong differences in soil properties then the park needs different management packages.

In conducting the soil tests, four steps were involved: 1) collection of representative soil samples, 2) analysis of the samples in a soil testing laboratory, 3) development of soil properties map using IDW interpolation, and 4) validation of the hypothesis.

Materials and Methods

Study Site

The 1.7 km² study site is selected in the Eastern Lagoon Mangrove National Park, Abu Dhabi, which is the first protected area in the United Arab Emirates (UAE). The study of the site is characterized by hot arid climate conditions, a high saline seawater environment, nearly flat topography, and several interconnected tidal creeks. The mangrove stand in the study site is inundated by tides twice daily (diurnal). During high tide, seawater completely covers the soil surface. The main vegetation cover in the forest includes grey mangroves (*Avicennia marina*) and salt marshes (*Arthrocnemummacrostachyum*). The average height of the trees is about three meters and can reach up to seven meters in some areas (Alsumaiti, 2014). The study site is contained within a rectangle defined by latitude and longitude of an upper left-hand corner at 24°27'20"N and 54°25'18"E and a lower right-hand corner at 24°26'52"N and 54°26'24"E (Figure 1).

Soil Properties Investigation

Ideally, soil sampling involves selection of individuals from a population to estimate the entire population's properties. A sampling design entails the most effective and efficient method of choosing samples, which will in turn aid in estimating the population properties. Therefore, the first salient step in the soil testing is the collection of soil samples (Carter & Gregorich, 2006). Several methods of soil sampling are applicable including stratified sampling, stratified systematic unaligned sampling, random sampling, as well as stratified random sampling. In the current study, the stratified systematic unaligned sampling method was used (Figure 2). This method combines randomness and stratification with a systematic interval. In this way, it

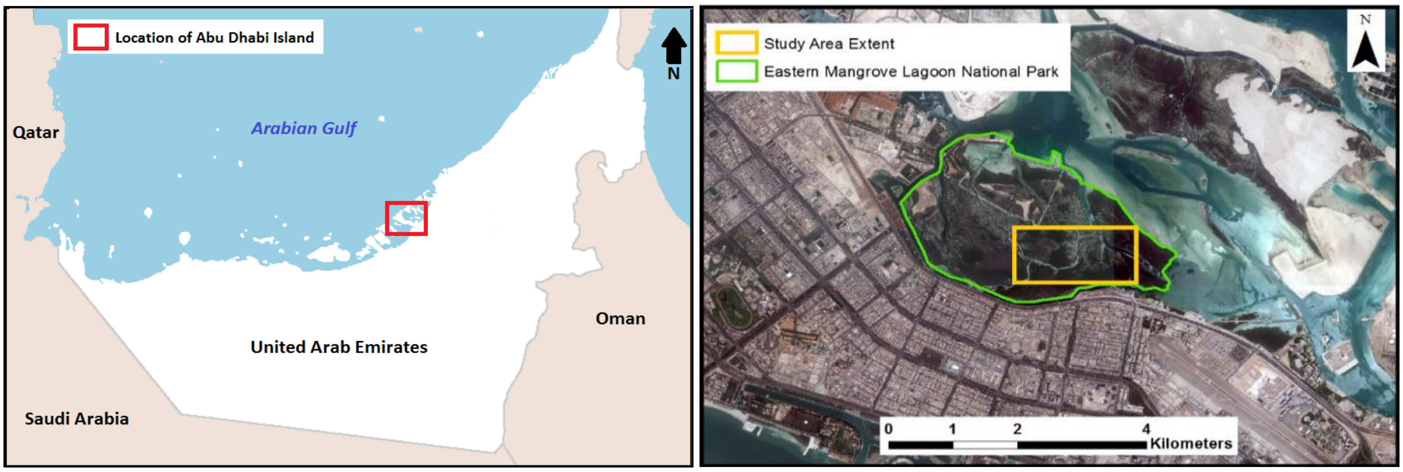

Figure 1: The left map represents the location of Abu Dhabi Island (red box), while the right map represents the location of the study area (yellow box) within Eastern Mangrove Lagoon National Park (green polygon) in Abu Dhabi, UAE.

Introduces more randomness than just starting with x, y coordinate for the first sample in each stratum (Jensen, 2005). The soil investigation was successfully conducted (from February to April 2014), despite the difficulties experienced in getting deep sub-surface soil samples in mangrove swamps. The extensive root system and the high-water table limited the sampling depth to around one meter. The holes dug in the swamps tended to fill with water in seconds because of the considerably high-water table. Mostly, mangrove soil occurs as a very soft liquid mass (slaked mud) and shows modest profile differentiation up to this depth.

A total of 36 sites were located in the study area using Global Positioning System (GPS) equipment (Figure 2). Accordingly, for each site, soil samples were collected using standard soil sampling augers at two depths (0-50 cm and 50-100 cm). Thus, a total of 72 soil samples were collected from 36 locations. About one kilogram of the soil sample from each location was obtained, and then placed in a clean plastic bag and labeled. Subsequently, the samples were sent to the laboratory for analysis to determine their important physical and chemical characteristics.

Laboratory Analysis of Soil Samples

Laboratory analysis of the soils is necessary to verify the collected data to determine soil characteristics that cannot be estimated accurately based on in situ observation. The laboratory analysis of the 72 samples was conducted at the Central Analytical Laboratory

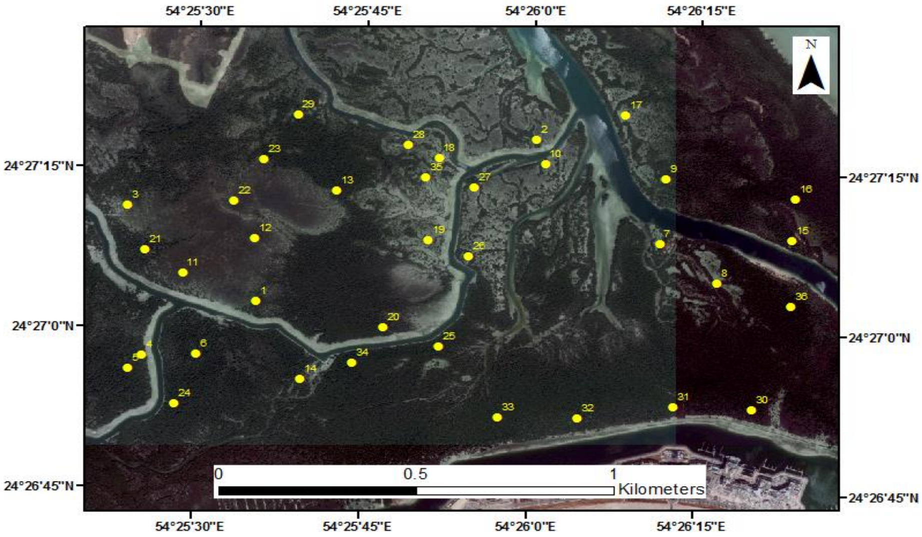

Figure 2: The locations of soil sampling sites in the study area.

(CAL) of the Dubai based International Center of Biosaline Agriculture (ICBA). The analysis was performed using the standard procedures from the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) as described in the Soil Survey Laboratory Methods Manual (Burt 2004). The soil analysis included the testing of soil physical and chemical characteristics, nutrient status, and organic matter content. Prior to soil analyses in the laboratory, soil samples were air-dried and then ground to pass a 2 mm sieve. No graves were found in soil samples. Below is a brief description of the soil analysis procedures used in this soil investigation.

Soil Texture

Soil texture is the percent distribution of sand (2-0.05 mm), silt (0.05-0.002 mm) and clay (< 0.002 mm) in a soil sample (< 2mm). Prior to soil texture analyses, the materials which pose a problem in achieving soil dispersion (organic matter, gypsum, soluble salts, and calcium carbonates) should be removed. Since the soil samples from mangrove sites are extremely rich in $CaCO_3$, removing the high amounts of $CaCO_3$ will cause the soil texture to not be representative. Under such conditions, feel test method is used to have an apparent soil texture. In this test, a small volume of water is added to a small handful of soil and then mixed to form a ball until it starts sticking to the analyst's hand. The ball is transformed into different shapes to confirm soil texture.

Soil Chemical Analysis

A soil analysis was performed on air-dried soil samples and the results were presented on oven-dried soil basis. The following tests were performed to estimate soil chemical properties:

➢ *Soil Reaction or Hydrogen Ion Activity (pH):* Soil pH measures the level of soil alkalinity or acidity, which plays an essential role in controlling the nutrient availability and fixation in the soil (Shahid et al., 2014). A standard pH meter calibrated using buffer solutions was used to measure the pH of saturated soil paste (pHs).

➢ *Electrical Conductivity of the Saturated Soil Paste Extract (ECE):* The electrical conductivity is a standard representation of an indirect measurement of soil salinity, which is an important indicator of the health of the soil (Shahid et al., 2014). Electrical conductivity is related to the number of salts which are more soluble than gypsum in the soil, although it may contain a small contribution from dissolved gypsum (up to 2 dS/m) (Soil Survey Division 1993). A standard and calibrated EC meter was used to measure ECe, which is reported as DeciSiemens per meter (dS/m).

➢ *Soil Solution Chemistry:* This is determined by measuring the ionic composition of soil saturation extract. Using standard titration procedures and equipment such as Flame photometer, the major concentration of cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}) are determined.

➢ *Calcium Carbonate Equivalents (CCE):* CCE refers to the calcium carbonates (calcite) and its equivalents ($MgCO_3$, $CaMg\ (CO_3)_2$ etc.) in the soil. Calcium carbonate, a common substance found in rocks, is the main component of marine organisms' shells (Keller, 2007). Calcium carbonate equivalents are vital in controlling the buffering capacity (resistance in soil pH change) of soil as well as nutrients availability. To measure the calcium carbonate level in the soil, the sample was treated with hydrochloride acid (HCl). The evolved carbon dioxide (CO_2) was measured manometrically using a calcimeter. Then, the carbonate amount was calculated as percent calcium carbonate equivalent regardless of the carbonate's form in the soil sample (e.g. dolomite, sodium carbonate, magnesium carbonate, etc.).

➢ *Sodium Adsorption Ratio (SAR):* SAR, which indicates the relative concentration of sodium to calcium and magnesium in the soil saturation extract, expresses the relative activity of sodium ions in the exchange reactions with the soil (Stahl & Ramadan, 2011). SAR indicates the balance between the amount of sodium in saline solution and exchangeable sodium, which adheres to the soil exchange complex (Shahid et al., 2014). The SAR was calculated using the following standard formula:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+}+Mg^{2+})}}$$

Using inputs for the water-soluble cations expressed as mill equivalents per liter (meq/l), and SAR expressed as $(mmoles/l)^{0.5}$.

Soil Fertility

Soil fertility refers to the amount of major nutrients in the soil including nitrogen, phosphorus, and potassium. The NPK are measured using the following procedures.

- Nitrogen (N): Standard Kjeldahl equipment was used to measure the amount of nitrogen. The sample was digested at high temperature and then the nitrogen was distilled and absorbed in acid which was measured through standard titration.
- Phosphorous (P): The amount of phosphorous was determined calorimetrically after using a standard sample preparation procedure.
- Potassium (K): The amount of potassium was measured in 1N ammonium acetate extract by a Flame photometer.

Soil Organic Matter

Plant and animal remains at different decomposition states in addition to the products of root exudation and cells and tissues of soil organisms, make up soil organic matter. Soil organic matter has several positive impacts on soil's physical and chemical properties, and on soil's capacity to regulate the ecosystem (Brady & Weil, 1999). The presence of organic matter is important for the quality and function of the soil. For upland soils, the amount of organic matter content normally ranges from 1% to 6% of the total topsoil mass. While for desert soils, the total topsoil mass contains less than 1% organic matter (Troeh & Thompson, 2005). Soil organic matter acts as a major sink and source of soil carbon. Organic carbon capacity to affect plant growth, both as an energy source and as a catalyst to make nutrients available, makes organic carbon an important constituent of the soil (Edwards et al., 1999). Soil organic matter was determined by igniting the samples at 450°C after they have been dried at 105°C to remove the moisture. The amount of weight loss after ignition was then determined to estimate organic matter contents (Storer, 1984).

Creation of Spatial Soil Properties Maps

Spatial soil properties maps can be prepared using two approaches; 1) Kriging and 2) Inverse distance weighted (IDW). In our study we used IDW method as this was considered appropriate for the type of soil data collected in the present study. IDW interpolation determines cell values using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be that of a locationally dependent variable. This method assumes that the variable being mapped decreases in influence with distance from its sampled location (ESRI (Arcgis.com).

Results and Discussions

The results from the present study are presented in various forms (bar diagrams, digital images, and IDW interpolation) and formed the basis of discussion and conclusions. The results of soil characteristics are also tested against a hypothesis "*similar characteristics at the study site*" to support a management plan of mangrove forestation in the Eastern lagoon mangrove national park. The most important soil characteristics from mangrove habitats are soil texture, salinity-ECe, sodicity-SAR and $CaCO_3$ contents across the study site and at depths, and hence are presented and discussed first, following by other characteristics.

Soil Texture of Mangroves Sediments

Seven soil texture classes have been identified in the study area. These are loamy sand (21.6%), silt loam (21.6%), light clay (17.6%), sand (12.1%), clay loam (10.8%), heavy clay (9.5%), and loam (6.8%) (Figure 3). There are significant differences in soil texture among the sites and at different layer depths. At 0–50 cm depth, finer texture-light clay soil and clay loam are the most dominant soil texture types; while at 50–100 cm depth, coarser texture-loamy sand, sand, and silt loam are the main types of soil texture (Figures 3 & 4). Most of the sites are characterized as 'duplex' soils (finer texture at surface underlain by coarse texture at subsurface). Similar soil texture in mangrove swamps have been reported by Lacerda (2002). This is due to the development of mud in mangroves area over a long period of time in different phases under tidal affects and deposition of wind borne material. Perhaps at an earlier stage, there was a high contribution of sand deposits (from sea and wind), and then the coarser material transformed to finer material through physical weathering or through settling of fine particles at surface through sedimentation in suspension. The maps in Figure 4, created using IDW interpolation, show the spatial distribution of soil texture in the study area.

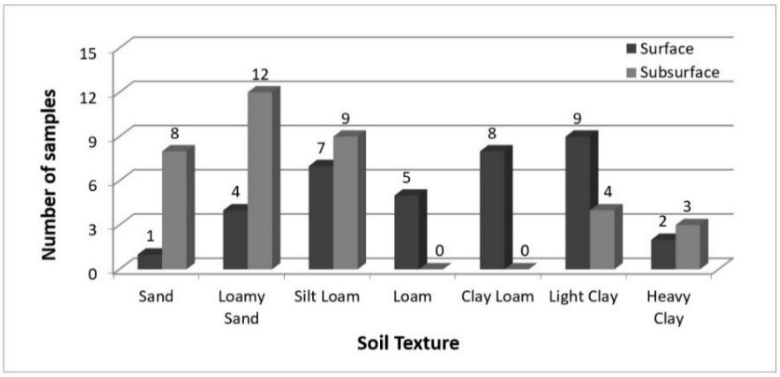

Figure 3: In depth soil texture classes of mangroves sediments.

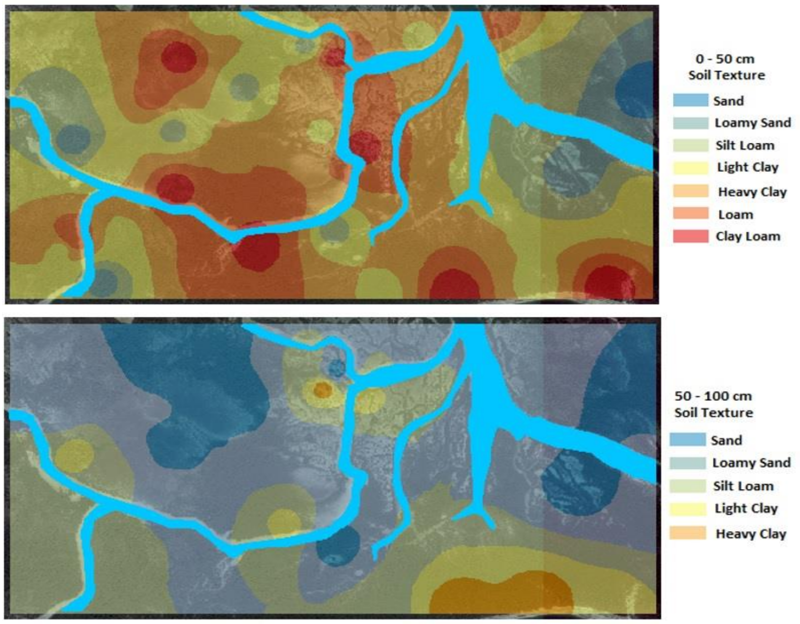

Figure 4: IDW interpolation of soil texture heterogeneity in the study site at two depths 0-50 and 50–100 cm.

Soil Salinity Assessment of Mangrove Sediments

Soil salinity is the main soil characteristic of mangrove mud due to direct exposure to seawater during tidal coverage. Mangrove soils are usually high in soil salinity. We tested the hypothesis by determining the level of soil salinity of two depths and comparing with the properties of a salic horizon. The Soil Survey Staff (2014) defines sialic horizon as below:

A salic horizon is a horizon of accumulation of salts that are more soluble than gypsum in cold water.

Required characteristics:

A sialic horizon is 15 cm or more thick and has, for 90 days or more in normal years:

- An electrical conductivity (EC) equal to or greater than 30 dS/m in the water extracted from a saturated paste and;
- A product of the EC, in dS m^{-1}, and thickness, in cm, equal to 900 or more.

The ECe values in the study site range from 48.6-75.6 dS/m (0-50 cm) with an average of 59.77 dS/m (SD ± 6.2) and 55.4-85.7 dS/m (50-100 cm) with an average of 66.64 dS/m (SD ± 7.4). Overall (0-100 cm) the ECe values range from 48.60 to 85.70 dS/m with an average of 63.20 ± 0.90 dS/m. There are some differences in soil salinity among the sites, while salinity levels slightly vary in different layer depths (Figures 5 & 6). Regardless of some differences in ECe values, all sites are classified as very strongly saline (ECe>40 dS/m) as per Soil Survey Division Staff (1993) classification, and as salic horizon classified as soil suborder-salids (Soil Survey Staff 2014; Shahid et al.,2014). Some of the soils have higher salinity values near the surface (0-50 cm), while other soils have higher salinity values at greater depths (50-100 cm). Figure 6 clearly shows that the lower salinity occurs near the intertidal creeks due to continuous contact with sea water and hence the salinity is diluted compared to the sites at distance from the creeks.

The salinities of the Arabian Gulf water are among the highest that have been measured in marine water, sometimes reaching as high as 57 dS/m (Bashitialshaaer et al., 2011). Interestingly, the salinity of mangrove soils in most sites exceeds the salinity of the marine water in the study area. This high concentration of the salts in the mangrove forest results from several factors including high frequency and duration of tidal inundation in the study area, very high temperature, high evaporation rate, and very low rainfall. According to Shahid et al. (2013), the climate of Abu Dhabi is extremely harsh and dry. In summer, the temperature is extremely high, and rainfall is close to zero, while winter is warm with little rainfall. However, the evaporation rate for the entire year exceeds rainfall many times over. The ratio of mean yearly evaporation to mean yearly rainfall is nearly 45 to 1. Theses harsh environmental conditions show that *Avicennia marina* in Abu Dhabi has a very high salt-tolerance, unlike many other mangrove species. Although most mangrove seedlings may require a low salinity level to survive, their salt tolerance increases as they grow (Bhosale, 1994). Yet, *Avicennia marina* can adjust up to twice salinity of the ocean seawater (Cintron et al., 1978).

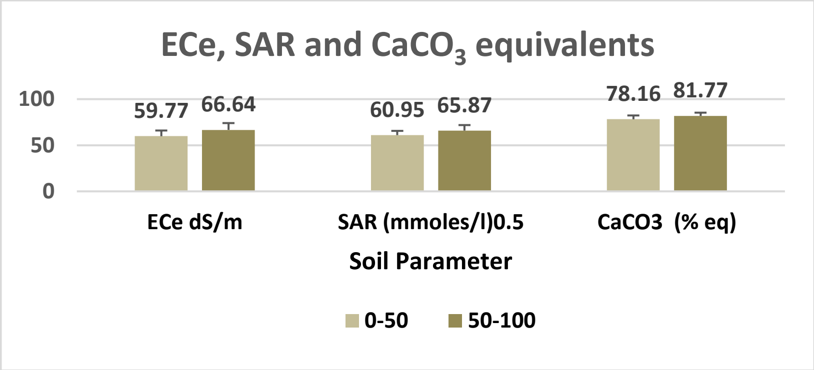

Figure 5: In depth comparison of ECe, SAR and $CaCO_3$ equivalents.

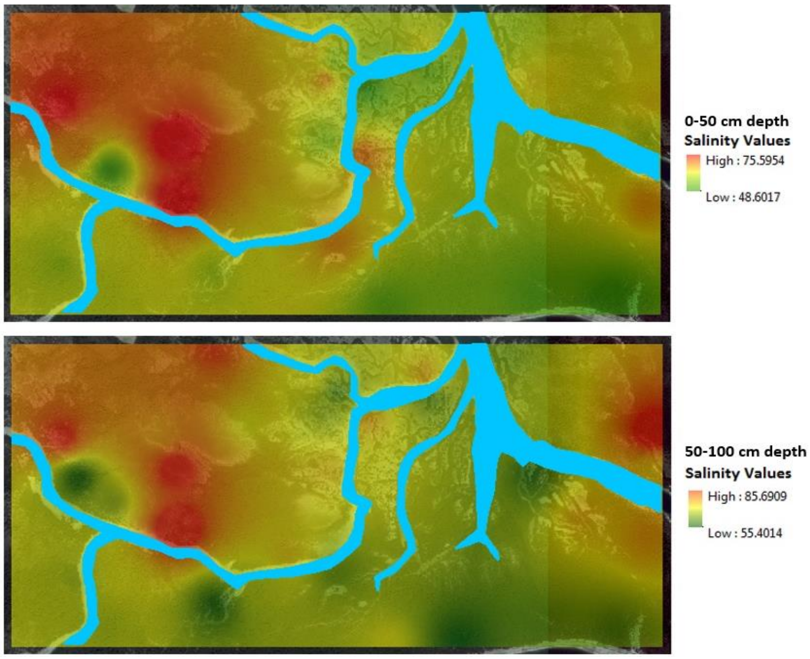

Figure 6: IDW interpolation of soil salinity (ECe) heterogeneity at 0 – 50cm and 50 – 100 cm depths.

Soil pH

The results of soil pH analysis indicate that 87.5% of the soil samples are in neutral pH range and 12.5% of the samples were slightly alkaline (Figure 7). The neutral pH occurs near the intertidal creek and increases at distance (Figure 8). The average pHs at 0-50 cm is 7.14 (SD ± 0.2) and at 50-100 cm 7.12 (SD ± 0.19). There are minor differences between pH levels at the two-layer depths. The pH values (0-100 cm) range from 6.78 to 7.72 with an average of 7.13 ± 0.02. Usually, soil pH values ranging from 6.7 to 7.3 are the most optimum values for the growth of mangrove trees. The values of soil pH varied slightly among the sites. The maps in Figure 8 show the spatial variation of pH levels in the study area.

In a recent study, Lim et al. (2012) mentioned that mangrove seedlings and trees can grow at their maximum rate even with a soil pH range from 5.16 to 7.72 because they can adapt to survive harsh environmental conditions and low nutrient availability. Still, mangroves, especially in germination stage, cannot tolerate extreme pH conditions (outside the range of 5.16 - 7.72) because they will cause nutrients to be inaccessible to the plants. The neutral pH range of most of the soil samples can be related to the dominance of neutral salt (Na and Cl) in the solution chemistry of soils from the study area. Figure 9 clearly illustrates the relative availability of main nutrients critical for plant growth at different pH levels. Most nutrients are most available for plant uptake when the soil pH is neutral (6.6-7.3) to slightly acidic (6.1-6.5). Soils with high pH values can limit iron availability resulting in iron chlorosis. Other nutrients such as manganese, copper, and zinc are also less available at high pH levels (Cooper T., 2009). Although pH values differ slightly among the sites, the majority of the sites fall into the neutral category where most of the nutrient is available to plants. This supports the hypothesis that sites within the Eastern lagoon mangrove national park are of similar characteristics.

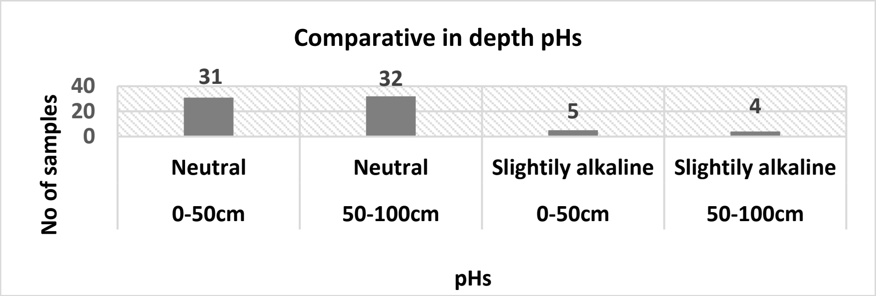

Figure 7: In depth comparison of pH of saturated soil paste (pHs).

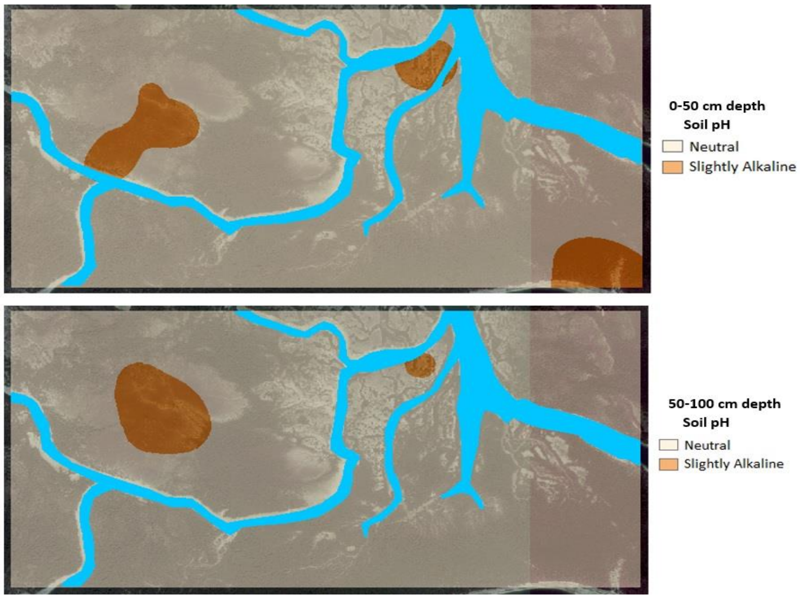

Figure 8: IDW interpolation of Soil pH heterogeneity at 0 – 50cm and 50 – 100 cm depths.

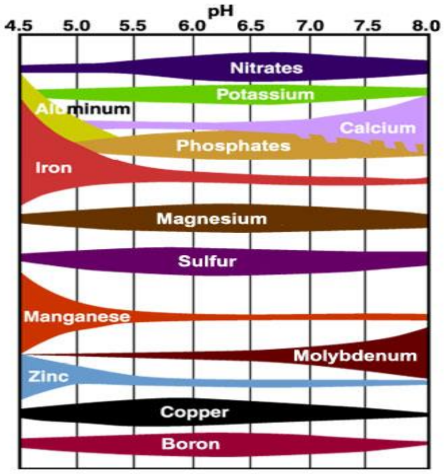

Figure 9: Effect of pH on nutrient availability to the plants. The band width shows the relative availability of each nutrient at different pH levels (Cooper T., 2009).

Soil Sodium Adsorption Ratio (SAR)

The SAR is measures of soil Na concentration relative to other soil cations (e.g. Ca, Mg), the elevated values for SAR indicate high Na. The sodium adsorption ratio (SAR) range from 53.57 (mmoles/l)$^{0.5}$ to 80.69 (mmoles/l)$^{0.5}$ with an average of 63.41 ± 0.7 (0-100 cm). The average SAR (0-50 cm) is 60.95 (SD + 1.62) and 65.87 (SD+6.01) at 50-100 cm. A soil with SAR levels higher than 13 is classified as sodic (Richards 1954). Since mangrove soils in the study area are characterized by high levels of both soluble salts and sodium, therefore, soils at all sites regardless of depth are classified as saline-sodic soil (Figure 10). These results support the hypothesis that one soil type occurs at all sites investigated in the Eastern lagoon mangrove national park. The IDW interpolation (Figures 5 & 10) show the similar pattern of SAR distribution at both the depths, lower being near the intertidal creeks and higher at distance.

Figure 10 presents the spatial variation in SAR at two depths. In most sites, the values of SAR increase with depth. This is because of seawater which has greater Na than other cations. High values of SAR and salts restrict the growth of many plants and affect properties of inland soils; however, their effect is reduced under submerged conditions. *Avicennia marina* has a great tolerance and can accumulate higher concentration levels.

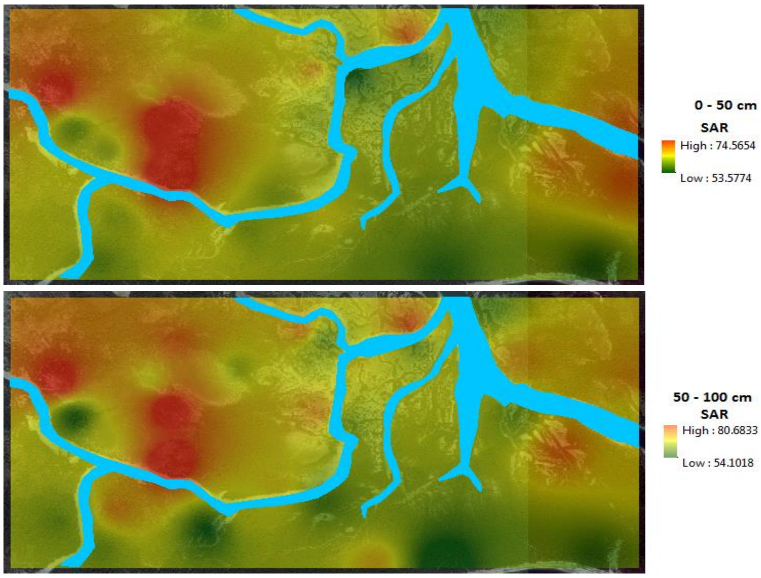

Figure 10: IDW interpolation of soil SAR heterogeneity at 0 – 50 cm and 50 – 100 cm depths.

Calcium Carbonate Equivalents

The results show that the percentage of calcium carbonate equivalents (CCE) in the soil samples ranges from 68.40 to 88.30% with an average of 79.96 ± 0.49%. Whereas Figure 5 shows, at 0-50 cm average $CaCO_3$ is 78.16% (SD ± 4.13) and at 50-100 cm (81.77% SD ± 3.57). The percentage of CCE increases with depth in most sites. The maps in Figure 11 show the spatial variation in the percentage of CCE at two depths. The $CaCO_3$ amounts in the study area are extremely high due to the high presence of marine organisms' remains and sea shells as observed in situ. The high amounts of the $CaCO_3$ result in high soil buffering capacity, which means that mangrove soils can absorb more acid without a major change in pH. The high buffering capacity, due to the presence of high $CaCO_3$ levels, stabilizes the pH (6.78-7.72) at all sites, which is slightly above the optimum range where most nutrients are available to plants. This limits the amounts of available essential nutrients to plants such as phosphorus. Additionally, the high amounts of $CaCO_3$ increase soil nitrogen (NH_4) losses through volatilization (Jones et al., 2007). The slight differences in $CaCO_3$ values within sites and at depths show the study site has similar characteristics. The hypothesis of similar soil characteristics across the Eastern lagoon mangrove national park is further tested using the criteria of soil mineralogy class "carbonatic" as defined by Soil Survey Staff (2014) and Shahid et al. (2014). The soil can be called carbonatic mineralogy class if it has more than 40 percent (by weight) carbonates (expressed as $CaCO_3$) plus gypsum, either in the fine-earth fraction (< 2mm) or in the fraction less than 20 mm in diameter, whichever has a higher percentage of carbonates plus gypsum. The results from the present study clearly show that all soil samples contain more than 40% $CaCO_3$ (68.44-88.3%), thus all sites investigated at both the depths are classified into one mineralogy class "carbonatic" and hence supporting the hypothesis of similar soil characteristics in Eastern Lagoon mangrove national park.

Nutritional Status of Mangrove Sediments

There are 16 essential nutrients required for plants to grow and develop properly. The three most vital nutrients are carbon (C), hydrogen (H) and oxygen (O_2), supplied from air and water (H_2O), while the other 13 nutrients are grouped into two main categories depending on the various amount needed for the plants. The first category is the macronutrients including N, P, K, S, Ca, and Mg, which are used in relatively large amounts. The

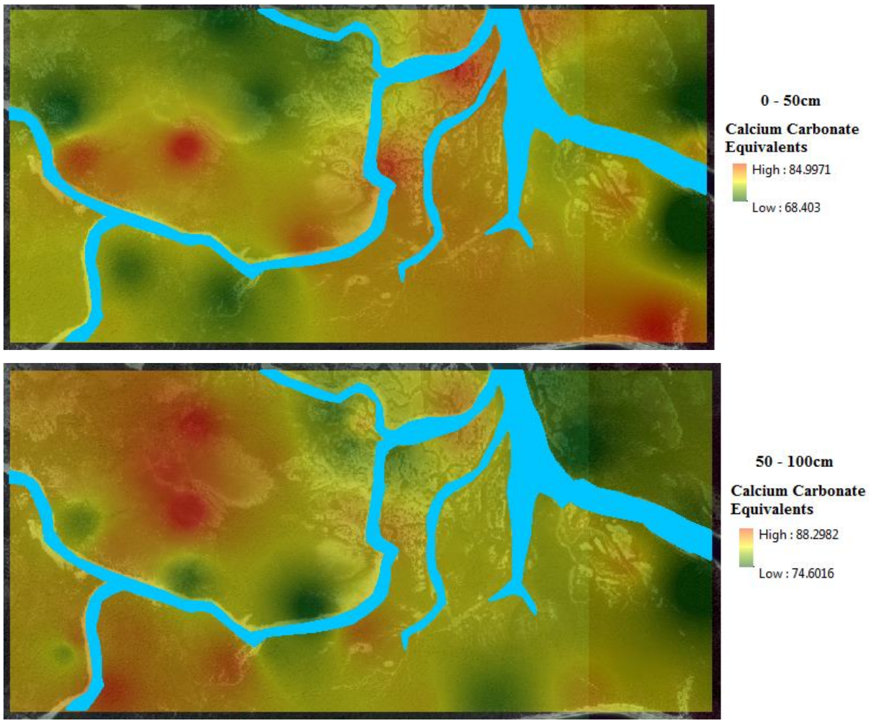

Figure11: IDW interpolation of calcium carbonates equivalents heterogeneity at 0 – 50cm and 50 – 100 cm depths.

second category is the micronutrients such as Zn, Cu, Fe, Mn, B, Cl, Mo, and Co, which are required in relatively small amounts. However, the micronutrients are just as important to plant development as the macronutrients. About 94% to 99.5% of fresh plant material is made up of the three essential nutrients C, H, and O_2, whereas the other nutrients make up the remaining 0.5% to 6%. In fact, nitrogen (N), phosphorus (P), and potassium (K) are the primary nutrients within the group of macronutrients (Barker &Pilbeam, 2006). Therefore, total N, available P, and available K are determined in the present study. Soluble K, which is dissolved in soil water, is also determined from soil saturation extract. Plants take up most of their potassium directly from soluble K.

The results show total nitrogen range from 34 to 1330 mg kg^{-1} (75 to 2926 kg ha^{-1}) with an average of 392 ± 34 mg kg^{-1}. In most sites, the amount of nitrogen increases with depth. Figure 12 shows the spatial variation of total nitrogen at different layer depths. Most of the soil samples (83%) are distributed between 101-1000 mg kg^{-1} (222-2200 kg ha^{-1}).The high concentration of nitrogen can be related to organic rich mud (plants and animals based) developed over many years. Nitrogen (N) is essential for plant growth and is taken up primarily as nitrate (NO_3^-) or ammonium (NH_4^+) ions (Galitz,1979). Plants utilize N to synthesize amino acids, which in turn form proteins. In fact, the protoplasm of all living cells contains protein. It is a component of chlorophyll, which gives the green color to plants and is vital for photosynthesis. The higher concentration of N and its availability to mangroves keeps the mangroves plantation healthy even under stress conditions (Reef et al., 2010).

Phosphorus (P) plays a key role in different plant functions such as photosynthesis and transfer of energy. Phosphorus is also essential in stimulating early root formation and growth, which helps the plants to hasten maturity rates as well as seed production (Fageria, 2008). It is absorbed by plants as $H_2PO_4^-$, HPO_4^{2-} or PO_4^{3-}, depending upon soil pH. Compared to total N contents, available P is significantly low and occurs in the range of 11-74 mg kg^{-1} (24 to 163 kg ha^{-1}) with an average of 44 ± 1.75 mg kg^{-1}. About 87% of the soil samples are distributed in the range of 20-60 mg kg^{-1} (44 to 132 kg ha^{-1}). However, the amount of available P decreases with depth on most sites. The maps in Figure 13 show the spatial variation of available P at different layer depths. The low amount of available phosphorous is due to P fixation with high amount of calcium carbonates in the soil (Qureshi and Jenkins, 1978), resulting in low P availability and efficiency to the plants unless acidic conditions prevail to release the fixed P. Using the electron probe micro analytical technique, Qureshi and Jenkins (1978) reported the presence of P as 0.3% in calcite ($CaCO_3$) grains. Shahid et al. (1992) have evaluated $CaCO_3$ distribution in soils using submicroscopic techniques and found $CaCO_3$ in eight morphological forms, most of these coating the soil pores which roots follow and found coating on the roots. Both features can inhibit P availability to plants.

Potassium (K), taken up by plants as potassium ion (K^+), is vital in different plants' processes and functions. For example, K activates many enzyme systems, which play an important role in carbohydrate and protein synthesis. It also reduces respiration, prevents energy loss, improves the water regime of the plant, and increases its tolerance to salinity and drought. The plants are less affected by diseases, if they are well supplied with K (Fageria, 2008). The results of the soil tests reveal higher concentration of ammonium acetate extractable (available) K ranging between 245-799 mg kg^{-1} (539 to 1757 kg ha^{-1}) compared to soluble K from soil saturation extract ranging between 156 to 198 mg kg^{-1} (343 to 436 kg ha^{-1}). About 75% of the soil samples are distributed in the range of 201 to 600 mg kg^{-1} (442 to 1320 kg ha^{-1}). The results also indicate that the amount of K decreases with depth in most sites. The maps in Figure 14 show the spatial variation of available K in study area at different layer depths.

The high K concentration in the soil can be attributed to two main reasons. The first is the organic rich mud and decomposed organic matter accumulated over a period by the special root system of the forest (pneumatophores), which releases K into soil. Second, K is part of the crystal structure of minerals such as mica and K-feldspar, which release K through weathering. It is believed that the higher concentration of K together with N keeps the mangroves green and healthy without the application of NPK (Nitrogen, Phosphorous, and Potassium) fertilizers (Reef et al., 2010).

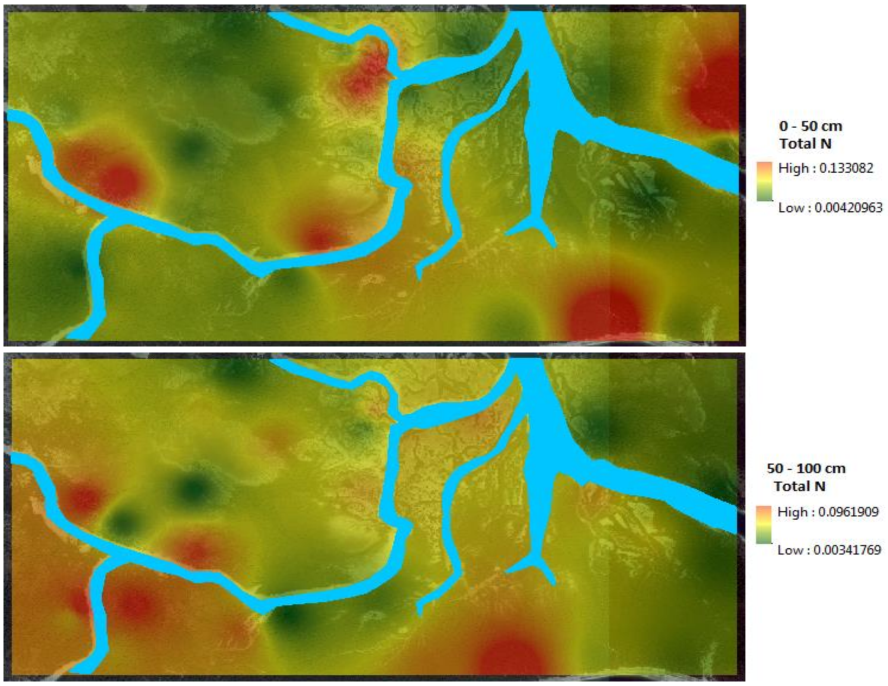

Figure12: IDW interpolation of total nitrogen heterogeneity at two depths created.

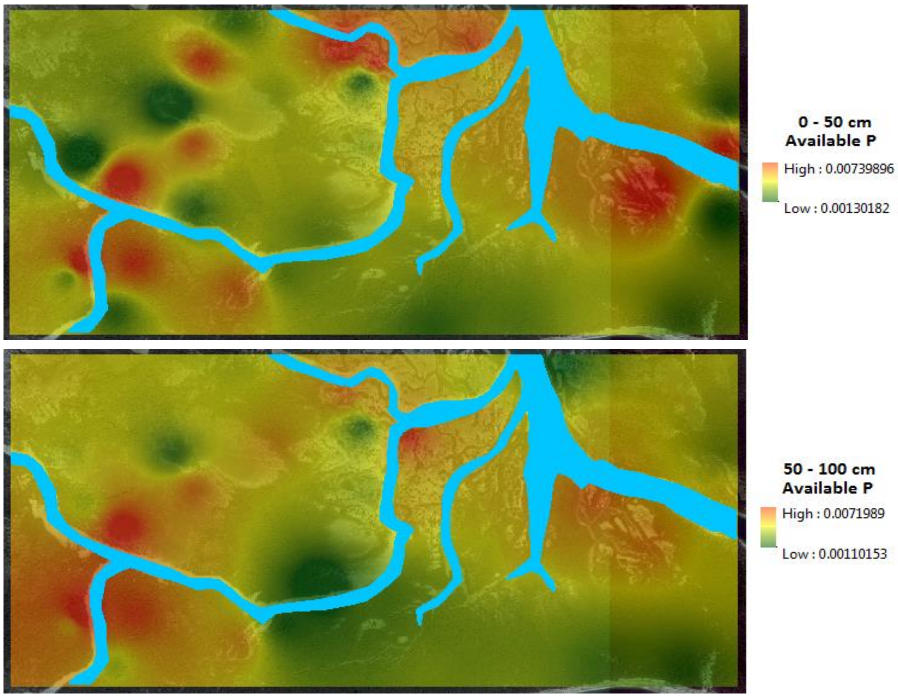

Figure 13: IDW interpolation of available phosphorous heterogeneity at two depths.

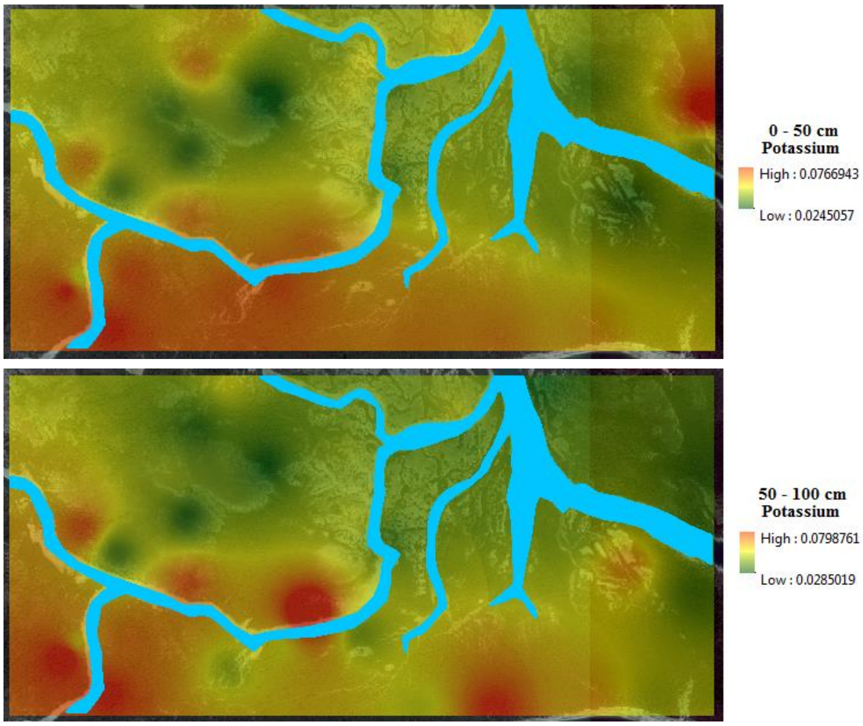

Figure 14: IDW interpolation of available potassium heterogeneity at two depths, 0-50 and 50-100 cm.

Soil Organic Matter

The results of the analysis indicate that mangrove soils are rich in organic matter content (Figure 15). The percentages of organic matter are high, ranging from 2.06 to 6.8% with an average of 3.56 ± 0.11%. There are significant differences in the amount of soil organic matter among the sites. The organic matter content also varies in different layer depths as seen in Figure 16. Some of the soils have higher OM% near the surface (0-50 cm), while few soils have a higher OM% at greater depth (50-100cm).

According to Shahid et al., (2013), the levels of organic matter in the soils of Abu Dhabi are generally very low due to the harsh arid environmental conditions. The amount of OM content in the soils of the most parts of Abu Dhabi is estimated to be about 0.2%. In contrast, as the results of the current work show, the soils of mangrove forests in Abu Dhabi have very high organic matter content. These high quantities of OM are due to the high densities of *Avicennia marina* (absolute total density was 143,896/ha). Higher OM content present in the soils is decomposed (mineralization) mostly from litterfall (e.g. leaves, bark, twigs, branches, etc.) and soil micro-organisms. According to Sukardjo (1994), soils composed of rich OM and soft mud sediments of fine silt and clay are important to the flourishing of mangrove

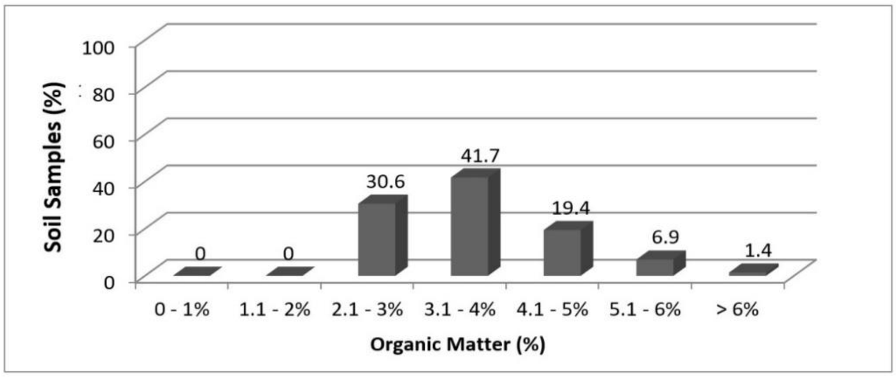

Figure 15: Frequency distribution of soil sample into different ranges of organic matter.

forests. Typically soils with the rich organic matter have a darker brown to black color. However, the soils in the study area have a very light color due to the high amounts of calcium carbonate.

The relatively high concentration of organic matter in mangrove soils compared to that of inland desert allows mangrove soils to have high carbon sequestration capacity, and thus lower greenhouse gases. The coastal mangroves sequester more carbon than any other ecosystem in the world (Alongi, 2002; Lucas et al., 2007). In fact, have the capacity to store carbon five times more than any other tropical forests per hectare. According to Eng (2011), mangrove soil has more carbon than most tropical forests have in their soil and biomass together. Such a high carbon-storing capacity is attributed partially to deep organic-rich mud in which mangroves thrive. The special root system (pneumatophores) of mangrove trees slows down tidal waters, which capture the organic material by allowing it to settle into the sediment surface, where low oxygen conditions of the sediments under mangrove swamps inhibits the decay process and results in greater carbon amounts to accumulate in the soil.

Conclusions

This study provides valuable information about mangrove soil properties which is critical for understanding and therefore preserving the mangroves. This study further supports the evaluation of soil variation effects on the spatial distribution of the mangrove trees through the conducted in situ soil survey. Soil maps were created to determine the key characteristics of soils and their influence on *Avicennia marina* spatial distribution.

This study indicates that the soils of Eastern Mangrove Lagoon National Park are fine in texture at the surface layer but coarser in texture at the subsurface layer. All soils are classified as very saline-sodic (very strongly saline and sodic) and salids suborder of the Aridisols soil order. This is due to the recognition of 'salic' horizon in all the sites. Both salinity (ECe) and sodicity (SAR) restrict the growth of many plants and affect soil properties. However, *Avicennia marina* has a very high salt-tolerance and can absorb higher concentrations of salts and exclude them through the leaves and tolerate high sodium levels due to the habitat

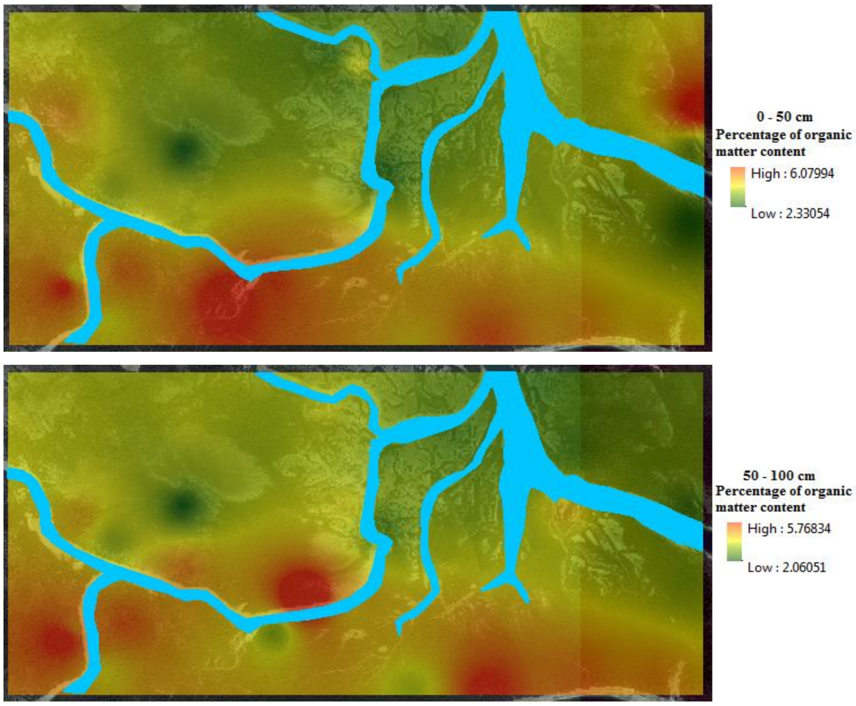

Figure 16: IDW interpolation of organic matter heterogeneity at two depths, 0-50 and 50-100 cm.

they thrive under the continuous influence of seawater. Additionally, the soils are characterized with extremely high amounts of $CaCO_3$ (carbonatic mineralogy class), which has buffered the pH between narrow range (6.78-7.72) ranging from dominantly from neutral to few sites as slightly alkaline. In the latter class, some of the nutrients (P) may be inhibited to plants. Conversely, the rich organic matter associated with soft mud sediments of fine silt and clay as well as the high availability of K and N supports mangrove forests' health and development. This study shows spatial variations in soil chemical characteristics in addition to the amount of organic matter content and the essential nutrients among the sites in the study area. However, when we tested the hypothesis of similar soil characteristics across the study site and at depths, it is concluded that the main soil characteristics (salinity-ECe; sodicity-SAR; $CaCO_3$) fall in the same categories interestingly such as salichorizpn (salids soil suborder), very high soil sodicity and carbonatic mineralogy class.This confirms the hypothesis that the study site regardless of some difference presents similar soil characteristics suggesting a management strategy of the entire mangrove site. It is also concluded that the areas with the lowest mangrove population have the lowest organic matter content and the lowest N and K concentrations; the same areas have the highest $CaCO_3$ amounts, and the highest salinity and pH levels. On the other hand, areas with the highest mangrove population have the highest organic matter content and the highest N and K concentrations; the same areas have the lowest $CaCO_3$ quantities, lowest SAR and ESP values, and lowest salinity and pH levels. These results indicate that soils' characteristics play a major role in the spatial distribution of Avicenna marina within the study area.

The good quality soil is needed for healthy growth and development of mangrove trees. Thus, ensuring that the three main nutrients (N, P, and K) are available to the plants is essential. Since the amount of P is low in the soils of the study area, P fertilizer should be added to soils. Even though very few researchers claim that the low P amounts should not limit the growth of mangrove trees (Sukardio, 1994), several experiments indicate that the availability of P is essential to the health of mangroves and that adding P to the soil has yielded increases in growth in mangroves (Neveu, 2013; Reef et. al., 2010). In addition to nutrient management at sites where very high SAR is recorded gypsum may be added to compensate the sodicity effects, this is not common practice, however, that is the only solution to reduce the soil sodicity effects and reducing the ratio between Cl and SO_4.

Moreover, living organisms, bacteria, and fungus are critical to healthy soil. For example, arbuscular mycorrhizal (AM) fungi help plants to absorb more water and nutrients including P from the soil (Smith et al. 2003). However, highly saline soils affect the occurrence of AM fungi, which negatively influences the uptake of some essential nutrients and could possibly increase the susceptibility to toxic metals. Very few researchers have studied the existence of AM fungi in the soils of mangroves (Sengupta&Chaudhuri, 2002; Kothamasi et. al., 2006). Therefore, future studies should evaluate the occurrence and distribution of AM fungi and other soil organisms to improve the quality of mangrove soils.

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