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Abu Dhabi Global Environmental Data Initiative

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Trial Assessment of Mangrove Soil Carbon Sequestration Rates in the United Arab Emirates

UAE Mangroves Annual Carbon Sequestration Project

Abu Dhabi Global Environmental Data Initiative (AGEDI) Ministry of Climate Change and Environment (MOCCAE)

The principal investigators for the UAE Mangroves Annual Carbon Sequestration Pilot Study are Dr. Stephen Crooks of Silvestrum Climate Associates, and Katrina Poppe of Western Washington University

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About the Report

In partnership with the Ministry of Climate Change and Environment, the project aims to quantify annual carbon sequestration rates of mangroves in the UAE through radiometric means: Lead-210 and Caesium-137. Such methods offer the most appropriate means to determine carbon sequestration rates for national inventories and coastal management planning.

The project findings aim to present an opportunity to incorporate carbon sequestration dating within national policies and strategies. This test pilot assessment of mangrove annual carbon sequestration rates in the UAE should be viewed as a highly exploratory and preliminary test case.

Future work on mangrove annual carbon sequestration rates can be advanced should the UAE choose to explore this concept further.

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A special thank you to the Principal Investigators, Dr. Stephen Crooks and Katrina Poppe, for their passion and dedication towards advancing blue carbon science, and for sharing their time and expertise.

We are grateful to Angela Rubilla who as well as managing this project for AGEDI was tirelessly helpful and good spirited in the field. We are grateful also to Jane Glavan (formerly of AGEDI) for initiating this project. We gratefully thank AGEDI for supporting the field work and contributing to regional and global blue carbon science.

EXECUTIVE SUMMARY

The UAE Mangrove Soil Carbon Sequestration Project is a follow up to the National Blue Carbon Project, commissioned by the Abu Dhabi Global Environmental Data Initiative (AGEDI) on behalf of the Environment Agency – Abu Dhabi (EAD). This project provides a trial to test determination of mangrove soil carbon sequestration rates across the Emirates using radiometric dating techniques. This and prior projects improve understanding of carbon storage and the other services that coastal and marine Blue Carbon ecosystems provide across the United Arab Emirates.

Radiometric dating by laboratory measurement of amounts of lead radioisotope (^{210}Pb) in the soil column, together with carbon density data, is the most effective means to determine soil carbon sequestration at the sub-century timescale. This information can be supplemented with identification of Caesium (^{137}Cs) deposits within sediments from historic nuclear emissions.

In discussions with the Environment Agency – Abu Dhabi, a decision was made, in a limited first phase, to focus on a single common landform, Khors (coastal lagoons) found in Abu Dhabi, Dubai, Ras al Khaimah and Sharjah. Sabkha and open coast remain unsampled. Field sampling was conducted in September of 2019 at five khors: Eastern Mangrove (Abu Dhabi), Ras Al Khor (Dubai), Khor Ras al Khaimah and Khor Hulaylah (Ras al Khaimah) and Khor Kalba (Sharjah). The research team worked closely with AGEDI, Environment Agency – Abu Dhabi (EAD), the Ministry of Climate Change and Environment (MOCCAE), and local government staff to select, access, and sample field locations. Two sites were selected from each khor. Where possible, the two sites from each khor were selected to compare a relatively healthy mangrove area to a degraded mangrove area (this was the case in Eastern Mangroves, Ras Al Khor, and Khor Ras Al Khaimah). Where only apparently healthy mangroves occurred throughout a Khor, the two sampling sites were selected from different areas of the forest (in Khor Hulaylah and Khor Kalba).

Standard field and analytical approaches were used to enable comparison with a growing global dataset on carbon sequestration rates in mangrove ecosystems. With five khors, two sites per khor, and one core per site, a total of 10 sediment cores were collected for this study. In the laboratory at Western Washington University, the sliced and dried cores were analyzed for bulk density and carbon density for each 2-cm depth cohort. Sediment accretion rates were determined from the downcore distribution of total and excess ^{210}Pb activity using gamma spectrometry. Downcore activity of ^{137}Cs was also analyzed to validate the ^{210}Pb results.

Carbon sequestration rates were calculated as the product of the sediment accretion rate and the mean C_{org} density in the top 30 cm of the core, which is approximately the depth range used for the ^{210}Pb accretion rate analysis.

The first two cores analysed, those of Khor Kalba (KK1 and KK2) were reported in the 2019 previous report. This report includes those two and adds results from the remaining eight sample cores, for a total of 10 cores across the UAE.

Sediment properties such as bulk density, organic matter, and C_{org} content, when averaged across the top 30 cm, varied substantially across sites and particularly across khors. Some sites displayed a thick organic peat layer before transitioning to inorganic carbonate sediments, while others showed less of a distinct peat layer and consequently lower soil carbon content. However, since bulk density is typically inversely related to C_{org} content, the product of the two resulted in low variability in C_{org} density across sites, with site C_{org} density ranging from 0.016 to 0.026 g C_{org} cm^{-3}.

Mean sediment bulk density was lowest at Khor Ras al Khaimah, RW1 (0.31 g cm^{-3}) and highest at Khor Hulaylah, AR2 (1.01 g cm^{-3}). Organic matter content was lowest at AR1 (6.37%) and highest at RW2 (31.82%). With C_{org} content strongly related to organic matter content, C_{org} content was also lowest at AR1 (2.12%) and highest at RW2 (14.45%).

Sediment accretion rates as measured with ^{210}Pb ranged from 0.05 cm yr^{-1} (Eastern mangroves, EM1) to 0.55 cm yr^{-1} (Ras Al Khor, RAK2). Only two of the 10 site ^{210}Pb profiles displayed obvious surface mixed layers to be removed from the accretion rate calculations. Site RW1 contained a 20-cm surface mixed layer, and EM2 contained a 2-cm mixed layer. All other sites showed a clear pattern of exponential decline of excess ^{210}Pb with depth. With the exception of one site below 0.1 cm yr^{-1} (EM1) and three sites above 0.4 cm yr^{-1} (RAK2, RW1, RW2), the majority of the sites showed very similar accretion rates averaging 0.19 cm yr^{-1}. Including those low and high rates resulted in an average accretion rate of 0.26 ± 0.01 cm yr^{-1} across all 10 sites.

The ^{137}Cs profiles generally lacked obvious peaks. There is reason to believe that ^{137}Cs may be less likely to produce viable results in saline, sandy environments such as are found in UAE, as these conditions increase ^{137}Cs mobility (Drexler et al. 2018, Foster et al. 2006). Mixed ^{137}Cs profiles were not accompanied by any apparent mixing in their corresponding ^{210}Pb profiles, suggesting that this is indeed an issue of high ^{137}Cs mobility rather than sediment mixing. We thus excluded ^{137}Cs profiles from our accretion rate analyses and conclude that ^{137}Cs may not be useful as a radiometric marker in the hypersaline mangroves of the UAE.

The ^{210}Pb accretion rates reported here are similar to the mean mangrove rate of 0.21 ± 0.09 cm yr^{-1} reported from the Saudi coast of the Arabian Gulf (Cusack et al. 2018), and the mean rate of 0.22 ± 0.06 cm yr^{-1} reported from the Saudi coast of the central Red Sea (Almahasheer et al. 2017). These rates are also comparable to global mangrove averages of 0.28 cm yr^{-1} (Breithaupt et al. 2012, Pérez et al. 2018).

Carbon sequestration rates ranged widely from 8.63 g C_{org} m^{-2} yr^{-1} (EM1) to 111.38 g C_{org} m^{-2} yr^{-1} (RAK2), with a mean of 57.67 ± 2.90 g C_{org} m^{-2} yr^{-1} across all 10 sites (Table 2; Figure 4). These rates are higher than other reported rates from this arid region, with 15 ± 1 g C_{org} m^{-2} yr^{-1} reported for Red Sea mangroves (Almahasheer et al. 2017) and 19 ± 11 g C_{org} m^{-2} yr^{-1} for western Arabian Gulf mangroves (Cusack et al. 2018). These rates are lower, however, than global mean sequestration rates of 163 g C_{org} m^{-2} yr^{-1} (Breithaupt et al. 2012) and 170 g C_{org} m^{-2} yr^{-1} (Pérez et al. 2018).

Interestingly, two of the highest accretion and carbon sequestration rates from this study were observed at degraded sites with poor drainage (RAK2 and RW2). Since these two sites are sparsely vegetated, the carbon deposited within them is most likely produced in adjacent healthy mangrove areas and later transported and collected in the degraded depressions along with the tide waters. Low oxygen conditions due to standing water may also reduce decomposition of this accumulated carbon. Carbon sequestration in these poorly drained mangrove areas may therefore be considered subsidized by neighboring healthy mangroves. However these pockets of slightly enhanced soil carbon sequestration can only persist while neighboring healthy mangroves remain present; the expansion of mangrove degradation to a larger proportion of the forest is expected to lower carbon sequestration rates due to lower total carbon production. Moreover, at Rak Al Khor poor drainage was associated with death of mangrove trees and so a total decline biomass carbon stock (not measured).

In addition to the poorly drained mangrove sites (RAK2 and RW2), the healthy site at Khor Ras Al Khaimah (RW1) also demonstrated relatively high accretion and carbon sequestration rates which may be the result of local water quality conditions (nutrient and freshwater inputs from adjacent urban areas highlighting benefit of linking mangrove restoration water sources of nutrients and freshwater.

Introduction

Project Context

“Blue Carbon” refers to the functional attributes of coastal and marine ecosystems to sequester and store carbon. Blue Carbon ecosystems of the United Arab Emirates (UAE) include mangrove forests, salt marshes and seagrass beds. Another potential Blue Carbon ecosystem identified as a result of prior projects are cyanobacterial “blue-green algal” mats (hereafter called algal flats). When these ecosystems are destroyed, buried carbon can be released into the atmosphere and ongoing sequestration is lost, contributing to global warming. In addition to their climate related benefits, Blue Carbon ecosystems provide highly valuable Ecosystem Services to coastal communities. They protect shorelines, provide nursery grounds for fish and habitats for a wide range of terrestrial and aquatic species, and support coastal tourism. They also have important cultural and social values.

A prior study, the Abu Dhabi Blue Carbon Demonstration Project quantified carbon stored and other services provided by coastal and marine Blue Carbon ecosystems along the Abu Dhabi coast. This contributed to the improved understanding of the relatively new concept of blue carbon on a regional and international level (Crooks et al., 2013; AGEDI, 2013; Crooks et al., 2014; AGEDI, 2014; Campbell et al., 2014; Schile et al., 2015).

This was followed up with a targeted assessment of mangrove carbon stocks across the northern Emirates (Kauffman and Crooks, 2015). These projects enhanced local capacity to measure and monitor carbon in coastal ecosystems and to manage associated data. The project also identified options for the incorporation of these values into policy and management to support sustainable ecosystem use and the preservation of their services for future generations.

Building on the results of the Abu Dhabi Blue Carbon Demonstration project, the current study tests an approach for quantifying soil carbon sequestration within mangroves of the United Arab Emirates. Five (5) khors were sampled (Eastern Mangroves, Abu Dhabi; Ras Al Khor, Dubai; Khor Ras Al Khaimah and Khor Hulaylah, Ras Al Khaimah; and Khor Kalba, Sharjah). Where areas of both healthy and degraded mangroves were identified within a given khor, one site was located in a healthy mangrove

area and one site in a degraded area to provide a pair-wise comparison of impacts of mangrove health on soil carbon stocks and sequestration rates. This approach resulted in two sites per khor, and one core per site, for a total of 10 cores.

Carbon sequestration was determined with radiometric methods (^{210}Pb). Such methods offer the most appropriate means to determine carbon sequestration rates for national inventories and coastal management planning. These new data points will inform future sampling to support the overall national Blue Carbon account for the UAE and across the region.

International Context

The Blue Carbon concept has strengthened interest in the management and conservation of coastal marine ecosystems, supporting climate change mitigation efforts. However, there are still gaps in the understanding of Blue Carbon, and incentives and policies are needed to ensure more sustainable environmental management practices.

The experience and knowledge gained from the project will help guide other Blue Carbon projects and international efforts, such as the International Blue Carbon Initiative[1] and the Global Environment Facility's (GEF) Blue Forests Project, of which AGEDI is a partner. This project also has helped develop Blue Carbon science and data management through the production of tools and the testing of methodologies that can be utilized and up-scaled to the international arena to enhance international Blue Carbon cooperation and training.

Project Setting

The marine and coastal environment of the United Arab Emirates hosts a myriad of marine organisms, living in diverse and unique environmental habitats (MOCCAE, 2015). For generations, the people of the UAE have relied on the coastal and marine environment as one of their main sources of income (MOCCAE, 2015). With the vision and direction from His Highness the late Sheikh Zayed Bin Sultan Al Nahyan, the natural environment has become an intrinsic part of the heritage and culture of the people of the UAE.

This national affinity to the sea has led to the initiation of the prior Abu Dhabi Blue Carbon Demonstration project and extension projects to the Northern Emirates in order to explore the values which coastal ecosystems provide the UAE, and to help preserve our environmental and cultural heritage. This project is commissioned by the Abu Dhabi Global Environmental Data Initiative (AGEDI) on behalf of EAD and support of the Ministry of Climate Change and Environment.

Science Team

The Principal investigator of this study is a member of the International Blue Carbon Scientific Working Group. Hosted by Conservation International, the International Union for Conservation of Nature (IUCN), and the Intergovernmental Oceanographic Commission (IOC), this working group of scientists assists in the building of capacity for the understanding of carbon cycling by coastal marine ecosystems. The Science Working Group runs in parallel with the International Blue Carbon Policy Working Group under the Blue Carbon Initiative.

The goals of the Science Working Group are to:

1) Assess the feasibility of coastal Blue Carbon as a conservation and management tool and its potential for climate change mitigation;
2) Provide implementable recommendations for coastal marine conservation and management that maximizes sequestration of carbon and avoids emissions in coastal systems;
3) Establish a network of demonstration projects to quantify carbon stocks and fluxes, test protocols for monitoring, reporting and verification.
4) Promote and support scientific research on carbon cycling by coastal Blue Carbon ecosystems

Dr. Stephen Crooks is a founder of Silvestrum Climate Associates, a US-based environmental consultancy. He is a practitioner in wetlands restoration and specializes in planning for climate change adaptation and mitigation. He is a founder of the Blue Carbon Initiative, and member of both the International Blue Carbon Scientific and Policy Working Group, a member of the Intergovernmental Panel on Climate Change (IPCC) Expert Working Group developing supplementary guidance for national greenhouse gas accounting to include wetlands, a Steering Committee Member of the IUCN Species Survival Commission (SSC) Mangrove Specialist Group, and an AFOLU expert for Wetland Restoration and

[1] http://thebluecarboninitiative.org/

Conservation category under the Verified Carbon Standards (VCS) Registry. He is the Source Lead to the US Environment Protection Agency with responsibility coastal wetlands in the National GHG Inventory of Emissions and Sinks.

Ms. Katrina Poppe is a Research Associate at Western Washington University with 9 years of experience as an estuarine ecologist, focusing on coastal blue carbon research in marsh, seagrass, and forested coastal wetlands, as well as coastal ecogeomorphology and sediment dynamics, and restoration monitoring. Katrina has led blue carbon lab analyses (including radioisotope analyses for accretion rates) for a number of projects from a variety of coastal environments.

Dr. John Rybczyk, Professor, has over 30 years of experience as an estuarine geomorphologist/ecologist in the United States and internationally, including extensive blue carbon research experience. Dr. Rybczyk has served as technical advisor for project laboratory work.

Capacity Building

During the course of this project, the research team was joined in the field by the staff of AGEDI, including experts and volunteers from the Environment Agency - Abu Dhabi, Dubai Municipality, Ministry of Climate Change and Environment, Ras Al Khaimah Environment Protection and Development Authority, and Sharjah Environment and Protected Areas Authority. Training was provided on sample collection methods.

A meeting was held at the Ministry of Climate Change and Environment with senior staff to discuss the project as well as observations on the health of mangroves.

Study Area

The coastline of the United Arab Emirates contains a mosaic of productive ecosystems, including coastal sabkha (broad, flat intertidal and supratidal flats without vascular plants), mudflats, microbial mats, mangroves, seagrasses, sporadic salt marshes and soft coral reefs. Mangroves are found along the margins of Sabkha and around the islands of Abu Dhabi, but more so in shallow coastal lagoons (Khors) to the north of Abu Dhabi and across the Northern Emirates. Much of the coast of the Sea of Oman is devoid of mangroves though small pocket estuaries provide a valuable ecological refuge, most notably at Khor Kalba.

The UAE is an arid country. Air temperatures seasonally range from 12ºC to 50ºC and water temperatures at the coastal margin ranging between 10ºC to 36ºC (EAD, 2007). Average annual rainfall is <100 mm and much less than evaporation rates of 1000 – 2000 mm. Salinity in the Arabian Gulf is high due to restricted tidal exchange and high rates of evaporation. Lower salinities are found on the ocean coast of the Emirates as well as in localized areas at urban water outflows, through drainage wadis and upwelling seeps at the base of mountains.

With the exception of a few planted Rhizophora saplings, the UAE hosts a single species of mangrove, *Avicennia marina*. *Avicennia marina* is a robust species, capable of tolerating the temperature fluctuations close to the most notherly latitudinal extent of mangrove forests and in environments with soil salinities up to 80 PSU (Crooks et al., 2013).

In khor settings mangroves have existed in the same location for decades and possibly centuries. At the same time, these khors are under stress from encroaching development, which is impacting the health of mangrove forests. Observations have been made by agency scientists of patches of dieback in mangrove forests.

Site Selection

This investigation studied carbon accumulation in mangrove soils from regionally representative khors. Five Khors were selected through discussions with staff from AGEDI and local agency partners. Two sites were selected from each khor, attempting to identify and contract apparently more healthy and less healthy locations (Table 1; Figure 1). Characterization of health was based upon agency staff experience, variation in interior mangrove cover observed from remotely sensed imagery and observations by the team in the field. Mass mortality of patches of mangroves in a forest interior (sometimes known as a mangrove heart attack) is often an indication of stress. This is exacerbated when only a single species is present as there is not the opportunity for a second species to occupy the open space created. Standing water in the mangrove during low tide is a clear driver of stress in a mangrove forest. The presence of barnacles on pneumatophores, roots trunks, and even branches may be an indicator that the mangrove is subject to high flooding frequencies.

Of the five khors studied here, three khors contained both healthy and degraded sites, while two khors appeared entirely healthy (Table 1). Site EM2 in Eastern Mangroves was considered degraded due to the presence of barnacles on mangrove trunk bases and on the soil surface, and numerous mangrove branches appearing brittle and decaying. The two other degraded sites, RAK2 (Ras Al Khor) and RW2 (Khor Ras Al Khaimah), were considered unhealthy primarily due to poor drainage. These sites were sparsely vegetated depressions surrounded by relatively healthy mangrove areas, with standing water at low tide and relatively soft, unconsolidated sediments.

Table 1: Site metadata for the sampled mangrove sites of the UAE

Site	Khor	Emirate	Site status	Collection date	Latitude (deg/min/sec)	Longitude (deg/min/sec)
EM1	Eastern Mangroves	Abu Dhabi	Healthy	9/2/2019	N 24° 27' 09.5"	E 54° 26' 22.5"
EM2	Eastern Mangroves	Abu Dhabi	Degraded	9/2/2019	N 24° 26' 44.2"	E 54° 25' 10.6"
RAK1	Ras Al Khor	Dubai	Healthy	9/3/2019	N 25° 11' 22.9"	E 55° 19' 30.3"
RAK2	Ras Al Khor	Dubai	Degraded	9/3/2019	N 25° 11' 23.3"	E 55° 19' 20.2"
RW1	Khor Ras Al Khaimah	Ras Al Khaimah	Healthy	9/4/2019	N 25° 46' 17.8"	E 55° 56' 54.7"
RW2	Khor Ras Al Khaimah	Ras Al Khaimah	Degraded	9/4/2019	N 25° 46' 13.3"	E 55° 56' 59.3"
AR1	Khor Hulaylah	Ras Al Khaimah	Healthy	9/4/2019	N 25° 53' 26.7"	E 56° 02' 01.3"
AR2	Khor Hulaylah	Ras Al Khaimah	Healthy	9/4/2019	N 25° 53' 41.8"	E 56° 02' 53.4"
KK1	Khor Kalba	Sharjah	Healthy	9/5/2019	N 24° 59' 57.8"	E 56° 21' 58.5"
KK2	Khor Kalba	Sharjah	Healthy	9/5/2019	N 24° 59' 29.6"	E 56° 22' 09.0"

Methods

Capacity Building

Field sampling was conducted in September of 2019. Cores were collected by manually driving PVC coring tubes (10 cm internal diameter) to a depth of 50 cm into the sediment with a mallet. The bottom edge of the coring tubes had been pre-sharpened to help cut through any belowground plant material. To check for any sediment compaction during coring, the height of the sediment surface was measured to the top of the corer both inside and outside the core before removal, although compaction was generally minimal to absent. Immediately upon removal, cores were capped in the field and transported in a vertical position. Cores were extracted from the tubes later the same day, sliced into 2-cm increments, and stored in 8-oz. screw-top tin jars that preserved sample dimensions. Samples were oven dried at 60°C before shipping.

Analytical

Immediately upon arrival at the WWU laboratory, sediment samples were oven dried again at 60°C until a constant mass was reached, to ensure that any moisture absorbed during transport had been removed. Samples were then weighed to determine dry bulk density:

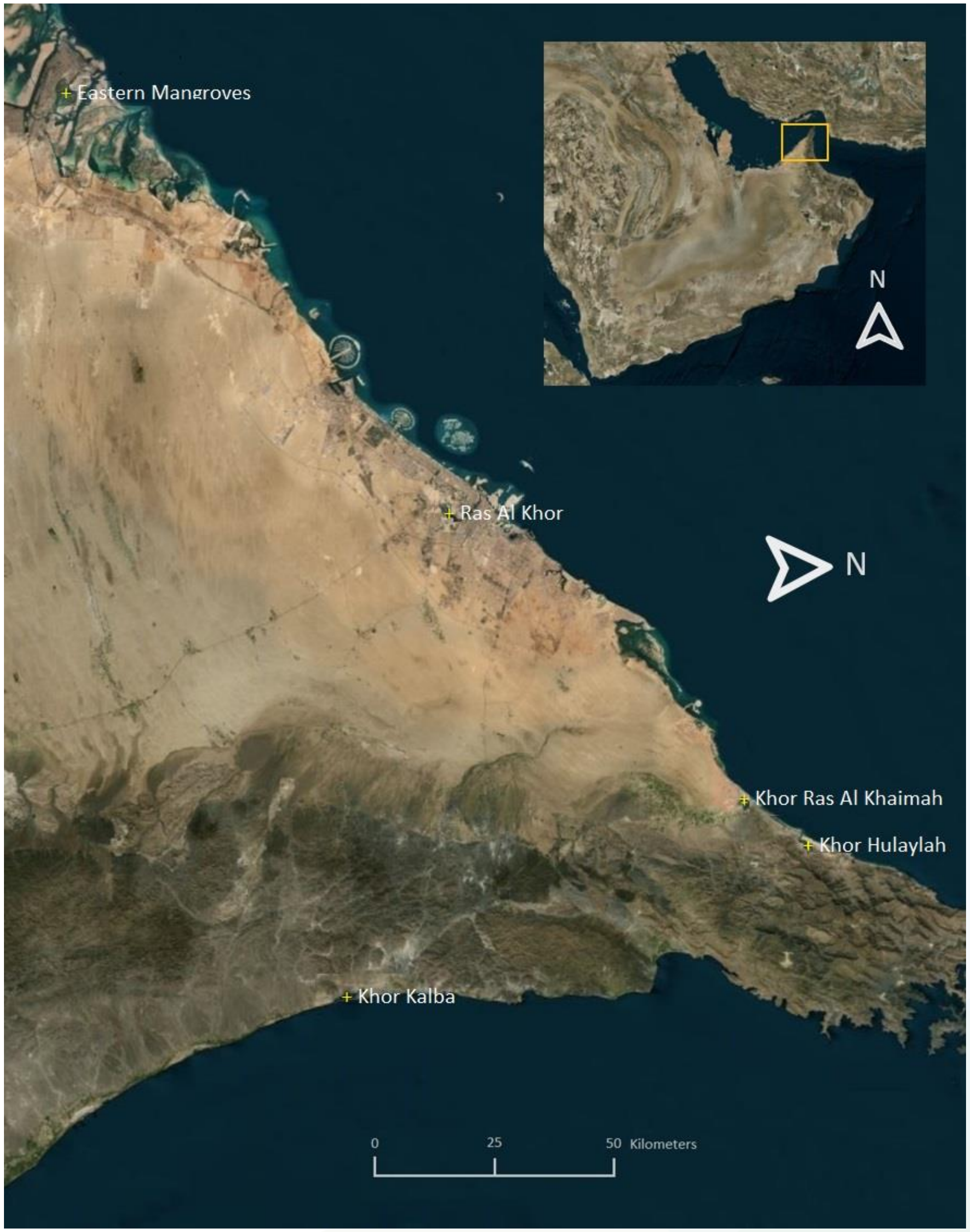
Bulk Density = Sample Dry Weight / Sample Wet Volume

Approximately half of each section was ground to a fine powder with mortar and pestle and passed through a 0.5-mm sieve. These ground subsamples were then used for the determination of organic content, carbon content, and radioisotope (^{210}Pb and ^{137}Cs) activity.

The organic matter (OM) content of each sample was determined by loss on ignition (LOI) using a Thermolyne furnace (type 48000). Approximately 12g of each subsample was burned at 500°C for 24 hours, and weighed before and after burning (Craft et al. 1991). Each sample's OM content was calculated as follows:

OM = Sample Dry Weight Before Burning – Weight After Burning * 100%

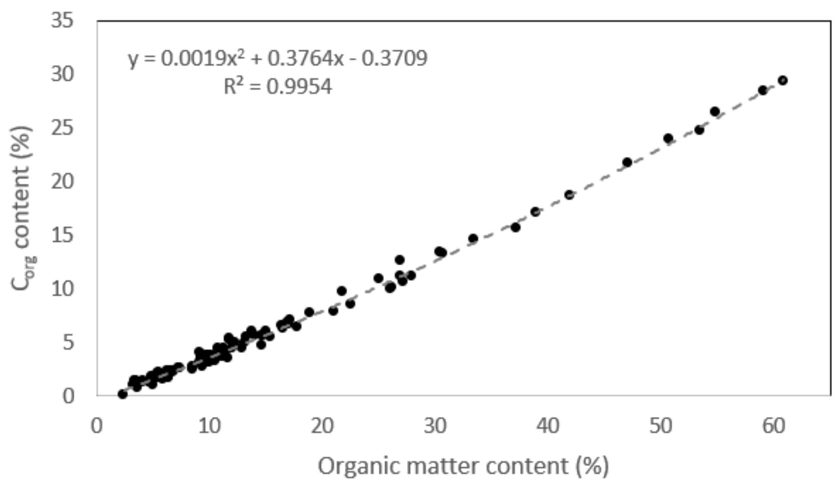
Figure 1: Sampling location map



Organic carbon (C_{org}) content was measured on a subset of samples (n = 100) with a FlashEA 1112 CN analyzer (Thermo Fisher Scientific, Waltham, MA). We first measured total carbon content (organic and inorganic combined), then isolated inorganic carbon from the ashed subsamples that remained after LOI, and finally calculated organic carbon content by subtraction. We developed an OM-C_{org} conversion from these 100 samples that was then applied to all sediment samples to produce the C_{org} contents reported here (Figure 2):

$$C_{org} = 0.0019 * OM^2 + 0.3764 * OM - 0.3709 \ (R^2 = 0.995)$$

Figure 2: Relationship between organic matter (OM) and organic carbon (C_{org}) content, based on a subset of 100 sediment core sections distributed across all cores and all depths.



Carbon density was calculated for each 2-cm core section as the product of bulk density and C_{org} content:

C_{org} Density = Bulk Density * C_{org} Content / 100%

Sediment accretion rates were determined from the downcore distribution of excess ^{210}Pb activity, providing an estimate of centennial-scale accretion rates assuming the depositional rate of excess ^{210}Pb does not change over time. We used a Canberra Germanium Detector (model GL2820R, Mirion Technologies (Canberra) Inc., Meriden, CT), with gamma emissions recorded by Genie 2000 software (Canberra 2002) at 46 keV and 351 keV.

Excess (unsupported) ^{210}Pb was calculated as the difference between total ^{210}Pb activity (at 46 keV) and supported ^{210}Pb activity (at 351 keV) to distinguish between excess ^{210}Pb deposited at the surface and supported ^{210}Pb that has decayed from radium in the sediment. Approximately 25 g of dried and ground subsamples from various depths through the sediment cores were analyzed. Each sample was analyzed for 48 to 72 hours, until the counting error rates for total and supported ^{210}Pb dropped at least below 10% and ideally below 5%. With 48 to 72 hours required per sample, and multiple samples from various core depths to analyze, this typically totals 3 to 4 weeks per core. With the constant initial concentration (CIC) model (Robbins et al. 1978), a linear regression of the natural log of excess ^{210}Pb activity versus depth was used to determine the sediment accretion rate:

Accretion Rate = $-\lambda / s$

where λ is the half-life of ^{210}Pb (22.2 yr^{-1}), and s is the slope of the regression.

Downcore activity of ^{137}Cs was also analyzed to validate the ^{210}Pb results. Unlike ^{210}Pb, ^{137}Cs is not naturally occurring, but rather was deposited as fallout during nuclear weapons testing during the last century. ^{137}Cs activity was recorded at 662 keV simultaneously with the ^{210}Pb activity measurements. A downcore peak in ^{137}Cs activity is assumed to coincide with the peak of nuclear testing in 1963. The sediment above this layer is then assumed to have accumulated at a constant rate since 1963. If a distinct ^{137}Cs peak cannot be identified, this suggests ^{137}Cs mobility throughout the soil column due to high permeability, or displacement by highly charged monovalent cations such as sodium and potassium (Drexler et al. 2018, Foster et al. 2006), which would make ^{137}Cs an inappropriate tool for dating in this situation.

To account for different spectrometer counting efficiencies at different energy levels, a calibration standard was analyzed for each core. The standard was created by adding approximately 0.5 g pitchblende silica-ore standard (CRM 103-A, New Brunswick Laboratory, USDOE) to a previously analyzed sample.

Carbon sequestration rates were calculated as the product of the sediment accretion rate and the mean C_{org} density in the top 30 cm of the core, which is approximately the depth range used for the ^{210}Pb accretion rate analysis:

C_{org} Sequestration Rate = Accretion Rate * Mean C_{org} Density *10,000

Results

Sediment properties such as bulk density, organic matter, and C_{org} content, when averaged across the top 30 cm, varied substantially across sites and particularly across khors (Table 2). Some sites displayed a thick organic peat layer before transitioning to inorganic carbonate sediments, while others showed less of a distinct peat layer and consequently lower soil carbon content (Figure 3). However, since bulk density is typically inversely related to C_{org} content, the product of the two resulted in low variability in C_{org} density across sites, with site C_{org} density ranging from 0.016 to 0.026 g C_{org} cm^{-3}.

Mean sediment bulk density was lowest at RW1 (0.31 g cm^{-3}) and highest at AR2 (1.01 g cm^{-3}) (Table 2). Organic matter content was lowest at AR1 (6.37%) and highest at RW2 (31.82%). With C_{org} content strongly related to organic matter content, C_{org} content was also lowest at AR1 (2.12%) and highest at RW2 (14.45%).

Sediment accretion rates as measured with ^{210}Pb ranged from 0.05 cm yr^{-1} (EM1) to 0.55 cm yr^{-1} (RAK2) (Table 2). Only two of the 10 site ^{210}Pb profiles displayed obvious surface mixed layers to be removed from the accretion rate calculations. Site RW1 contained a 20-cm surface mixed layer, and EM2 contained a 2-cm mixed layer. All other sites showed a clear pattern of exponential decline of excess ^{210}Pb with depth (Figure 4). With the exception of one site below 0.1 cm yr^{-1} (EM1) and three sites above 0.4 cm yr^{-1} (RAK2, RW1, RW2), the majority of the sites showed very similar accretion rates averaging 0.19 cm yr^{-1}. Including those low and high rates resulted in an average accretion rate of 0.26 ± 0.01 cm yr^{-1} across all 10 sites.

The ^{137}Cs profiles generally lacked obvious peaks. There is reason to believe that ^{137}Cs may be less likely to produce viable results in saline, sandy environments such as are found in the UAE, as these conditions increase ^{137}Cs mobility (Drexler et al. 2018, Foster et al. 2006). Mixed ^{137}Cs profiles were not accompanied by any apparent mixing in their corresponding ^{210}Pb profiles, suggesting that this is indeed an issue of high ^{137}Cs mobility rather than sediment mixing. We thus excluded ^{137}Cs profiles from our accretion rate analyses and conclude that ^{137}Cs may not be useful as a radiometric marker in the hypersaline mangroves of the UAE.

The ^{210}Pb accretion rates reported here are similar to the mean mangrove rate of 0.21 ± 0.09 cm yr^{-1} reported from the Saudi coast of the Arabian Gulf (Cusack et al. 2018), and the mean rate of 0.22 ± 0.06 cm yr^{-1} reported from the Saudi coast of the central Red Sea (Almahasheer et al. 2017). These rates are also comparable to global mangrove averages of 0.28 cm yr^{-1} (Breithaupt et al. 2012, Pérez et al. 2018).

It is difficult to determine if UAE mangrove accretion rates are sufficient to keep pace with sea level rise (SLR) when regional observations of SLR are limited. However, Siddig et al. (2019) reported local SLR measurements from the west coast of the Arabian Gulf averaging 0.23 cm yr^{-1} (1979 – 2008), compared with satellite altimeter-based trends of 0.36 cm yr^{-1} for the Arabian Gulf and 0.28 cm yr^{-1} globally (1993 – 2018). Although the rate of SLR can vary regionally due to differences in vertical land movement, those reported rates from the western Arabian Gulf may provide some indication of expected rates on the UAE coast. The average accretion rate of 0.26 cm yr^{-1} is roughly comparable to available SLR rates for the Arabian Gulf, suggesting that most UAE mangroves may be accreting sediment at a rate that keeps pace with sea level rise.

Results

Carbon sequestration rates ranged widely from 8.63 g C_{org} m^{-2} yr^{-1} (EM1) to 111.38 g C_{org} m^{-2} yr^{-1} (RAK2), with a mean of 57.67 ± 2.90 g C_{org} m^{-2} yr^{-1} across all 10 sites (Table 2; Figure 5). These rates are higher than other reported rates from this arid region, with 15 ± 1 g C_{org} m^{-2} yr^{-1} reported for Red Sea mangroves (Almahasheer et al. 2017) and 19 ± 11 g C_{org} m^{-2} yr^{-1} for western Arabian Gulf mangroves (Cusack et al. 2018). These rates are lower, however, than global mean sequestration rates of 163 g C_{org} m^{-2} yr^{-1} (Breithaupt et al. 2012) and 170 g C_{org} m^{-2} yr^{-1} (Pérez et al. 2018).

Interestingly, two of the highest accretion rates from this study were observed at degraded sites with poor drainage (RAK2 and RW2), leading to high carbon sequestration rates at these sites as well. Since these two sites are sparsely vegetated, the carbon deposited within them is most likely produced in adjacent healthy mangrove areas and later transported and collected in the degraded depressions along with the tide waters. Low oxygen conditions due to frequent inundation may also reduce decomposition of this accumulated carbon. Carbon sequestration in these poorly drained mangrove areas may therefore be considered subsidized by neighboring healthy mangroves. However this subsidy can only persist while neighboring healthy mangroves remain present; the expansion of mangrove degradation to a larger proportion of the forest is expected to lower carbon sequestration rates due to lower total carbon production.

In addition to the poorly drained mangrove sites (RAK2 and RW2), the healthy site at Khor Ras Al Khaimah (RW1) also demonstrated relatively high accretion and carbon sequestration rates which may be the result of local water quality conditions. The two Khor Ras Al Khaimah sites were located near a channel, with a layer of green algae on the sediment surface. Healthy mangroves were also particularly dense and tall, suggesting nutrient inputs to the mangroves from the adjacent urban areas, which may also be a source of freshwater. Higher nutrient and freshwater inputs are known to boost *Avicennia* spp. productivity under certain conditions (Naidoo 2006, Suárez & Medina 2005), providing another possible explanation for the high carbon sequestration rates in Khor Ras Al Khaimah.

Table 2: Mean sediment properties in the top 30 cm, centennial-scale accretion rates, and carbon sequestration rates for 10 mangrove sites across the UAE.

	Mean Bulk Density (g/cm^3)	Mean Organic Matter Content (%)	Mean C_{org} Content (%)	Mean C_{org} Density (gC/cm^3)	^{210}Pb Accretion Rate (cm/yr)	Sequestration Rate ($gC/m^2/yr$)
EM1	**0.97**	**8.61**	**3.17**	**0.016**	**0.05**	**8.63**
± SE	0.11	2.44	1.08	0.001	0.01	2.27
EM2	**0.79**	**8.31**	**2.91**	**0.020**	**0.17**	**34.00**
± SE	0.07	0.84	0.35	0.001	0.02	4.41
RAK1	**0.81**	**13.26**	**5.33**	**0.019**	**0.19**	**35.00**
± SE	0.12	3.77	1.73	0.002	0.03	5.37
RAK2	**0.52**	**12.89**	**4.85**	**0.020**	**0.55**	**111.38**
± SE	0.06	1.41	0.59	0.001	0.10	20.56
RW1	**0.31**	**22.47**	**9.08**	**0.026**	**0.41**	**106.44**
± SE	0.03	1.11	0.51	0.001	0.05	12.20
RW2	**0.36**	**31.82**	**14.45**	**0.023**	**0.46**	**105.75**
± SE	0.08	5.88	2.94	0.001	0.03	7.97
AR1	**0.92**	**6.37**	**2.12**	**0.018**	**0.20**	**35.41**
± SE	0.06	0.66	0.27	0.001	0.05	9.53
AR2	**1.01**	**9.13**	**3.36**	**0.020**	**0.13**	**25.02**
± SE	0.12	2.21	0.97	0.001	0.01	1.74
KK1	**0.89**	**9.21**	**3.27**	**0.025**	**0.27**	**67.41**
± SE	0.07	0.76	0.32	0.001	0.03	6.53
KK2	**0.57**	**11.91**	**4.39**	**0.025**	**0.19**	**47.63**
± SE	0.02	0.52	0.22	0.001	0.02	3.91

Figure 3: Soil profiles of organic carbon (C_{org}) content (% by weight).

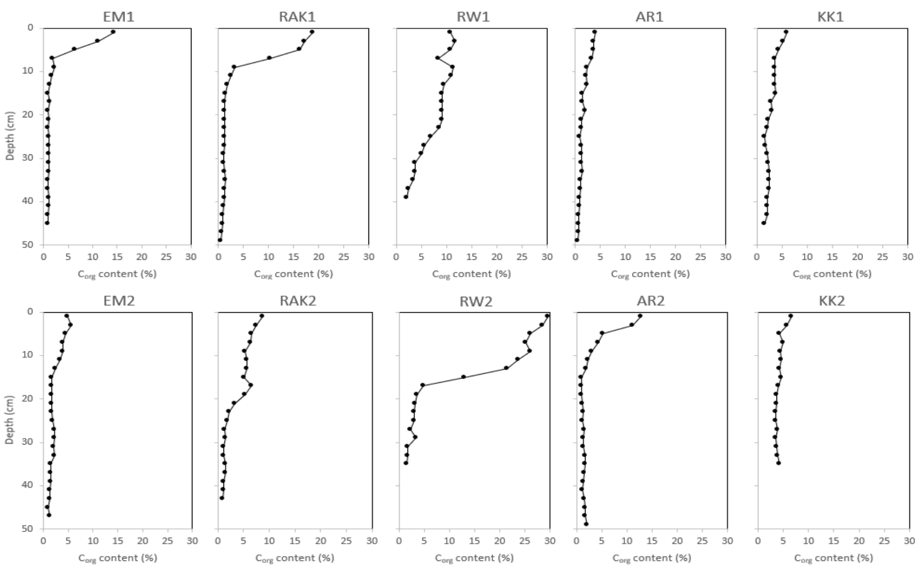


Figure 4: Soil profiles of excess ^{210}Pb (± 1 S.D.). Hollow points represent either mixed layers or negative excess ^{210}Pb values that were excluded from the accretion rate calculations.

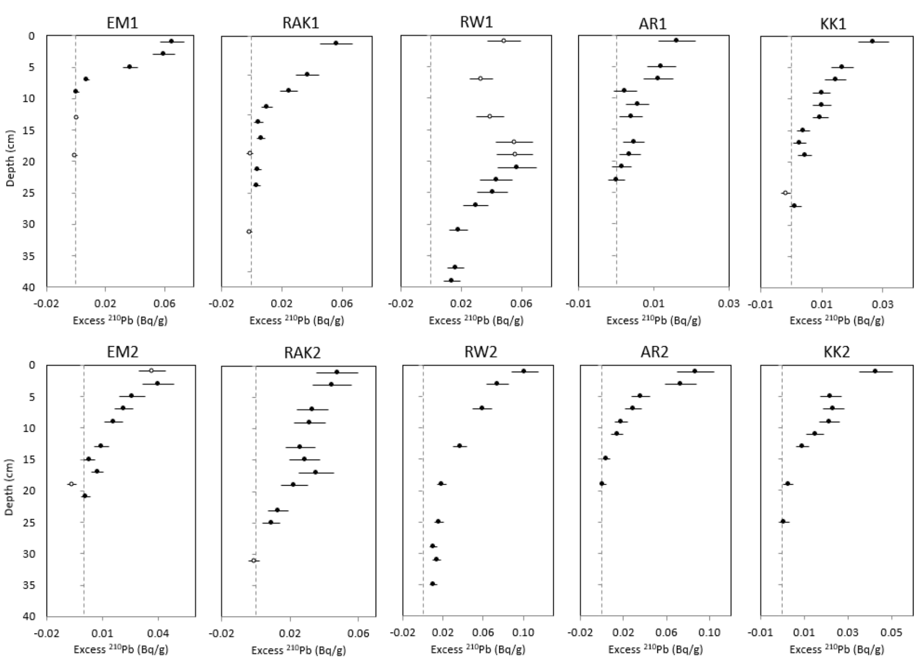
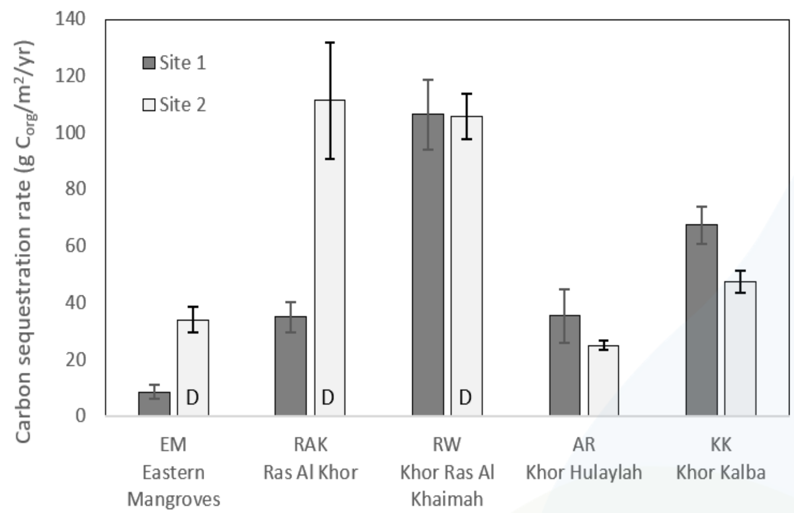


Figure 5: Carbon sequestration rates from five UAE khors, with two sites per khor. Within each khor, Site 1 was generally located in an apparently healthy mangrove area and Site 2 in a less healthy mangrove area, when possible. The three relatively degraded sites are labelled with "D". Error bars represent standard error.



Conclusions

These results have demonstrated that soil carbon sequestration rates can be gathered from the mangrove forests in the Khors of the United Arab Emirates.

Carbon sequestration rates from UAE mangroves (range 8.63 to 111.38 g C_{org} m^{-2} yr^{-1}; average 57.67 g C_{org} m^{-2} yr^{-1}) are meaningful rates for soil carbon sequestration given that they continue year after year as long as the mangrove remains healthy. As such the mangroves of the UAE are contributing to climate change mitigation. The values in khors are likely to be higher than mangroves found on open sabkha areas because of the high preservation potential found in accumulated muds of the khors. This may explain the greater rates found in the UAE relative to other reported rates around the Arabian peninsula, with 15 ± 1 g C_{org} m^{-2} yr^{-1} reported for Red Sea mangroves (Almahasheer et al. 2017) and 19 ± 11 g C_{org} m^{-2} yr^{-1} for western Arabian Gulf mangroves (Cusack et al. 2018). The UAE sequestration rates are lower, however, than global mean sequestration rates of 163 g C_{org} m^{-2} yr^{-1} (Breithaupt et al. 2012) and 170 g C_{org} m^{-2} yr^{-1} (Pérez et al. 2018) but in line with the CDM carbon finance Afforestation and Reforestation of Degraded Mangrove Habitat (AR-AM0014) methodology of 50 g C_{org} m^{-2} yr^{-1} or 0.5 t C_{org} ha^{-1} yr^{-1}. [2]

An additional note on mangrove carbon sequestration. The carbon that is sequestered supports many ecosystem services. The soil carbon helps to bind the sediments and adds to the volume enabling the soils to build vertically and maintain the mangrove against sea level rise. The carbon that is stored in the soils reflects only a part of the carbon extracted from the carbon dioxide from the atmosphere. A larger proportion flows from the plants and soils to support the food chain of the birds, fish and mammals found in mangroves and nearby coastal waters. Some of this carbon will be deposited elsewhere in the marine ecosystem and so represents an additional but unquantified amount of carbon sequestration from mangrove systems.

Finally, small forests are recognized to have outsized ecological value in coastal systems because they provide critical habitat in the life cycle of many marine species and, for this reason, they are of heightened conservation value (Curnick et al. 2019). It is recommended that the governments of the UAE conserve and restore mangrove forest to maintain the richness of the UAE coastal ecosystem.

[2] https://cdm.unfccc.int/methodologies/DB/KMH6O8T6RL3P5XKNBQE2N359QG7KOE

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Appendix A: Sediment Data

Table 3: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at EM1.

Eastern Mangroves (EM) 1					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.18	33.53	14.39	0.026
2-4	3.0	0.21	27.00	11.18	0.023
4-6	5.0	0.34	16.55	6.38	0.021
6-8	7.0	0.83	5.72	1.84	0.015
8-10	9.0	0.85	6.57	2.18	0.019
10-12	11.0	0.96	5.44	1.73	0.017
12-14	13.0	1.33	4.24	1.26	0.017
14-16	15.0	1.39	3.49	0.97	0.013
16-18	17.0	1.06	4.29	1.28	0.013
18-20	19.0	1.02	3.55	0.99	0.010
20-22	21.0	1.38	4.01	1.17	0.016
22-24	23.0	1.52	3.53	0.98	0.015
24-26	25.0	1.04	3.75	1.07	0.011
26-28	27.0	1.14	3.85	1.11	0.013
28-30	29.0	1.24	3.60	1.01	0.013
30-32	31.0	1.10	3.73	1.06	0.012
32-34	33.0	1.15	3.66	1.03	0.012
34-36	35.0	0.77	3.33	0.90	0.007
36-38	37.0	1.22	3.48	0.96	0.012
38-40	39.0	1.01	3.62	1.02	0.010
40-42	41.0	1.07	3.64	1.02	0.011
42-44	43.0	1.20	3.51	0.97	0.012
44-46	45.0	1.12	3.12	0.82	0.009
Mean (0-30 cm)		**0.97**	**8.61**	**3.17**	**0.016**
± SE		0.11	2.44	1.08	0.001

Table 4: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at EM2.

Eastern Mangroves (EM) 2					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.44	13.25	4.95	0.022
2-4	3.0	0.59	14.69	5.57	0.033
4-6	5.0	0.46	12.09	4.46	0.020
6-8	7.0	0.50	10.82	3.92	0.020
8-10	9.0	0.66	10.81	3.92	0.026
10-12	11.0	0.65	9.35	3.31	0.021
12-14	13.0	0.68	7.31	2.48	0.017
14-16	15.0	1.23	5.53	1.77	0.022
16-18	17.0	0.88	5.19	1.63	0.014
18-20	19.0	1.18	5.58	1.79	0.021
20-22	21.0	0.97	5.13	1.61	0.016
22-24	23.0	0.98	5.46	1.74	0.017
24-26	25.0	1.06	5.95	1.94	0.020
26-28	27.0	0.72	6.81	2.28	0.017
28-30	29.0	0.81	6.60	2.20	0.018
30-32	31.0	0.82	6.13	2.01	0.017
32-34	33.0	0.92	6.62	2.20	0.020
34-36	35.0	0.97	4.69	1.44	0.014
36-38	37.0	1.12	4.88	1.51	0.017
38-40	39.0	0.81	4.82	1.49	0.012
40-42	41.0	0.89	4.38	1.31	0.012
42-44	43.0	1.06	4.28	1.27	0.014
44-46	45.0	1.39	3.50	0.97	0.014
46-48	47.0	1.18	4.23	1.26	0.015
Mean (0-30 cm)		**0.79**	**8.31**	**2.91**	**0.020**
± SE		0.07	0.84	0.35	0.001

Table 5: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at RAK1.

Ras Al Khor (RAK) 1					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.13	42.02	18.80	0.025
2-4	3.0	0.18	39.02	17.21	0.032
4-6	5.0	0.21	37.29	16.31	0.034
6-8	7.0	0.29	25.12	10.28	0.030
8-10	9.0	0.51	9.36	3.32	0.017
10-12	11.0	0.74	7.36	2.50	0.019
12-14	13.0	0.78	5.55	1.78	0.014
14-16	15.0	1.00	4.87	1.51	0.015
16-18	17.0	1.03	4.33	1.29	0.013
18-20	19.0	1.36	4.28	1.27	0.017
20-22	21.0	1.27	4.03	1.18	0.015
22-24	23.0	0.75	4.04	1.18	0.009
24-26	25.0	1.16	4.05	1.19	0.014
26-28	27.0	1.30	3.95	1.15	0.015
28-30	29.0	1.44	3.61	1.01	0.015
30-32	31.0	1.34	3.73	1.06	0.014
32-34	33.0	1.10	4.18	1.23	0.014
34-36	35.0	1.30	4.65	1.42	0.018
36-38	37.0	1.52	4.26	1.27	0.019
38-40	39.0	1.45	4.09	1.20	0.017
40-42	41.0	1.60	3.92	1.14	0.018
42-44	43.0	1.28	3.25	0.87	0.011
44-46	45.0	1.27	3.46	0.95	0.012
46-48	47.0	1.74	2.90	0.74	0.013
48-50	49.0	1.52	2.49	0.58	0.009
Mean (0-30 cm)		**0.81**	**13.26**	**5.33**	**0.019**
± SE		0.12	3.77	1.73	0.002

Table 6: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at RAK2.

Ras Al Khor (RAK) 2					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.39	21.77	8.73	0.034
2-4	3.0	0.28	18.93	7.43	0.021
4-6	5.0	0.27	17.16	6.65	0.018
6-8	7.0	0.35	16.41	6.32	0.022
8-10	9.0	0.38	14.04	5.29	0.020
10-12	11.0	0.48	14.83	5.63	0.027
12-14	13.0	0.35	14.73	5.58	0.020
14-16	15.0	0.39	13.64	5.12	0.020
16-18	17.0	0.32	16.91	6.54	0.021
18-20	19.0	0.41	14.22	5.36	0.022
20-22	21.0	0.60	9.23	3.27	0.020
22-24	23.0	0.85	6.74	2.25	0.019
24-26	25.0	0.90	5.56	1.78	0.016
26-28	27.0	0.85	4.47	1.35	0.011
28-30	29.0	0.97	4.68	1.43	0.014
30-32	31.0	1.19	4.09	1.20	0.014
32-34	33.0	1.33	3.90	1.12	0.015
34-36	35.0	1.05	4.91	1.52	0.016
36-38	37.0	1.11	4.78	1.47	0.016
38-40	39.0	1.19	3.99	1.16	0.014
40-42	41.0	0.90	4.09	1.20	0.011
42-44	43.0	1.18	3.31	0.90	0.011
Mean (0-30 cm)		**0.52**	**12.89**	**4.85**	**0.020**
± SE		0.06	1.41	0.59	0.001

Table 7: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at RW1.

Ras Al Khaimah (RW) 1					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.29	26.27	10.83	0.032
2-4	3.0	0.26	28.02	11.67	0.030
4-6	5.0	0.15	26.10	10.75	0.016
6-8	7.0	0.38	21.07	8.40	0.032
8-10	9.0	0.16	27.16	11.25	0.018
10-12	11.0	0.28	26.62	11.00	0.030
12-14	13.0	0.25	23.29	9.43	0.024
14-16	15.0	0.31	22.44	9.03	0.028
16-18	17.0	0.24	22.75	9.18	0.022
18-20	19.0	0.26	22.63	9.12	0.024
20-22	21.0	0.35	22.81	9.21	0.033
22-24	23.0	0.31	21.53	8.61	0.027
24-26	25.0	0.31	17.88	6.97	0.021
26-28	27.0	0.49	14.74	5.59	0.028
28-30	29.0	0.57	13.65	5.12	0.029
30-32	31.0	0.49	10.52	3.80	0.019
32-34	33.0	0.71	10.29	3.71	0.026
34-36	35.0	0.78	9.49	3.37	0.026
36-38	37.0	0.94	7.27	2.47	0.023
38-40	39.0	1.02	6.39	2.11	0.022
Mean (0-30 cm)		**0.31**	**22.47**	**9.08**	**0.026**
± SE		0.03	1.11	0.51	0.001

Table 8: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at RW2.

Ras Al Khaimah (RW) 2					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.09	60.84	29.56	0.027
2-4	3.0	0.10	59.10	28.51	0.030
4-6	5.0	0.08	54.92	26.03	0.022
6-8	7.0	0.10	53.44	25.17	0.024
8-10	9.0	0.09	54.91	26.03	0.025
10-12	11.0	0.10	50.76	23.63	0.023
12-14	13.0	0.12	47.09	21.57	0.027
14-16	15.0	0.16	30.72	12.99	0.020
16-18	17.0	0.33	12.91	4.80	0.016
18-20	19.0	0.51	10.07	3.61	0.018
20-22	21.0	0.86	9.03	3.18	0.027
22-24	23.0	0.69	8.59	3.00	0.021
24-26	25.0	0.84	8.56	2.99	0.025
26-28	27.0	0.71	6.87	2.30	0.016
28-30	29.0	0.68	9.50	3.38	0.023
30-32	31.0	1.15	5.38	1.71	0.020
32-34	33.0	0.80	5.39	1.71	0.014
34-36	35.0	0.82	5.07	1.59	0.013
Mean (0-30 cm)		**0.36**	**31.82**	**14.45**	**0.023**
± SE		0.08	5.88	2.94	0.001

Table 9: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at AR1.

Khor Hulaylah (AR) 1					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.59	11.14	4.06	0.024
2-4	3.0	0.65	9.97	3.57	0.023
4-6	5.0	0.63	9.92	3.55	0.022
6-8	7.0	0.92	9.13	3.22	0.030
8-10	9.0	0.75	6.77	2.26	0.017
10-12	11.0	1.09	6.60	2.20	0.024
12-14	13.0	0.73	6.76	2.26	0.016
14-16	15.0	1.02	4.84	1.49	0.015
16-18	17.0	0.97	4.82	1.49	0.014
18-20	19.0	0.81	5.91	1.92	0.016
20-22	21.0	1.01	4.20	1.24	0.013
22-24	23.0	1.28	3.95	1.14	0.015
24-26	25.0	1.41	3.17	0.84	0.012
26-28	27.0	0.96	4.33	1.29	0.012
28-30	29.0	1.04	4.06	1.19	0.012
30-32	31.0	1.34	4.19	1.24	0.017
32-34	33.0	1.23	4.48	1.35	0.017
34-36	35.0	1.45	3.52	0.98	0.014
36-38	37.0	1.61	3.57	1.00	0.016
38-40	39.0	1.61	3.45	0.95	0.015
40-42	41.0	1.56	3.40	0.93	0.015
42-44	43.0	1.38	2.76	0.68	0.009
44-46	45.0	1.23	2.67	0.65	0.008
46-48	47.0	1.51	2.62	0.63	0.010
48-50	49.0	1.26	2.44	0.56	0.007
Mean (0-30 cm)		**0.92**	**6.37**	**2.12**	**0.018**
± SE		0.06	0.66	0.27	0.001

Table 10: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at AR2.

Khor Hulaylah (AR) 2					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.18	30.42	12.84	0.023
2-4	3.0	0.21	27.02	11.19	0.024
4-6	5.0	0.46	14.01	5.28	0.024
6-8	7.0	0.59	11.66	4.27	0.025
8-10	9.0	0.75	8.51	2.97	0.022
10-12	11.0	0.99	6.97	2.34	0.023
12-14	13.0	1.16	5.69	1.83	0.021
14-16	15.0	1.39	3.37	0.92	0.013
16-18	17.0	1.07	3.70	1.05	0.011
18-20	19.0	1.52	3.58	1.00	0.015
20-22	21.0	1.55	4.00	1.17	0.018
22-24	23.0	1.26	4.47	1.35	0.017
24-26	25.0	1.41	4.26	1.27	0.018
26-28	27.0	1.29	5.01	1.56	0.020
28-30	29.0	1.35	4.34	1.30	0.018
30-32	31.0	1.20	4.75	1.46	0.017
32-34	33.0	1.08	5.34	1.69	0.018
34-36	35.0	1.24	5.28	1.67	0.021
36-38	37.0	0.98	4.77	1.47	0.014
38-40	39.0	1.08	4.42	1.33	0.014
40-42	41.0	1.09	4.24	1.26	0.014
42-44	43.0	1.04	5.14	1.61	0.017
44-46	45.0	1.09	5.46	1.74	0.019
46-48	47.0	1.12	5.61	1.80	0.020
48-50	49.0	0.96	6.32	2.08	0.020
Mean (0-30 cm)		**1.01**	**9.13**	**3.36**	**0.020**
± SE		0.12	2.21	0.97	0.001

Table 11: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at KK1.

Khor Kalba (KK) 1					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	–	15.48	5.91	–
2-4	3.0	0.51	13.84	5.20	0.026
4-6	5.0	0.63	11.57	4.24	0.026
6-8	7.0	0.59	9.89	3.54	0.021
8-10	9.0	0.83	9.83	3.51	0.029
10-12	11.0	0.69	9.96	3.57	0.025
12-14	13.0	0.74	9.88	3.53	0.026
14-16	15.0	0.77	10.24	3.68	0.028
16-18	17.0	0.84	8.32	2.89	0.024
18-20	19.0	1.05	8.86	3.11	0.033
20-22	21.0	1.10	6.77	2.26	0.025
22-24	23.0	1.22	6.58	2.19	0.027
24-26	25.0	1.21	5.13	1.61	0.020
26-28	27.0	1.13	5.49	1.75	0.020
28-30	29.0	1.23	6.35	2.09	0.026
30-32	31.0	0.96	6.92	2.33	0.022
32-34	33.0	0.98	7.10	2.40	0.024
34-36	35.0	0.92	7.40	2.52	0.023
36-38	37.0	1.19	7.43	2.53	0.030
38-40	39.0	0.63	6.24	2.05	0.013
40-42	41.0	1.03	6.56	2.18	0.023
42-44	43.0	1.20	6.41	2.12	0.025
44-46	45.0	1.47	4.87	1.51	0.022
Mean (0-30 cm)		**0.89**	**9.21**	**3.27**	**0.025**
± SE		0.07	0.76	0.32	0.001

Table 12: Measured values of soil bulk density, organic matter content, organic carbon (C_{org}) content, and C_{org} density at KK2.

Khor Kalba (KK) 2					
Section	Mid-depth (cm)	Bulk Density (g/cm^3)	Organic Matter Content (%)	C_{org} Content (%)	C_{org} Density (gC/cm^3)
0-2	1.0	0.56	17.08	6.61	0.037
2-4	3.0	0.43	15.02	5.71	0.025
4-6	5.0	0.49	11.84	4.35	0.021
6-8	7.0	0.62	13.33	4.98	0.031
8-10	9.0	0.58	12.19	4.50	0.026
10-12	11.0	0.54	12.35	4.57	0.025
12-14	13.0	0.51	11.77	4.32	0.022
14-16	15.0	0.52	12.47	4.62	0.024
16-18	17.0	0.66	11.30	4.12	0.027
18-20	19.0	0.65	10.36	3.73	0.024
20-22	21.0	0.51	10.38	3.74	0.019
22-24	23.0	0.66	10.09	3.62	0.024
24-26	25.0	0.56	10.03	3.60	0.020
26-28	27.0	0.64	10.64	3.85	0.024
28-30	29.0	0.61	9.87	3.53	0.022
30-32	31.0	0.58	10.34	3.73	0.022
32-34	33.0	0.71	10.82	3.92	0.028
34-36	35.0	0.57	11.78	4.33	0.024
Mean (0-30 cm)		**0.57**	**11.91**	**4.39**	**0.025**
± SE		0.02	0.52	0.22	0.001