Abu Dhabi Global Environmental Data Initiative (AGEDI)

Abu Dhabi Blue Carbon Demonstration Project

Baseline Assessment Report: Coastal Ecosystem Carbon Stocks

Table of Contents

List of Tables

List of Figures

Executive Summary

Summary for Policy Makers

The Abu Dhabi Blue Carbon Demonstration Project aims to improve our understanding of carbon capture and storage (sequestration), and the other services that coastal and marine Blue Carbon ecosystems provide in the Emirate, and in addition, contribute to the improved understanding of this relatively new concept on a regional and international level. The project ultimately aims to present and utilise a science based approach to inform decisions, through policies and appropriate management, in particular in relation to sustainable ecosystem use and the preservation of their services for future generations.

Blue Carbon Ecosystems of the United Arab Emirates (UAE) include mangrove forests, salt marshes and seagrass beds. Another potential Blue Carbon ecosystem identified as part of this project is cyanobacterial "blue-green' algal" mats. This study is the first to investigate algal mats as a potential Blue Carbon ecosystem. A small set of samples were also collected from coastal sabkha. Although not a Blue Carbon ecosystem, historic soil carbon stocks that are likely to have a Blue Carbon origin were identified below the surface at some sites.

When these ecosystems are destroyed, buried carbon can be released into the atmosphere, which subsequently contributes to global warming. In addition to the climate related benefits of protecting and enhancing, these ecosystems also provide highly valuable *Ecosystem Services* to the coastal community. These include the protection of shoreline, provision of nursery grounds for fish and habitats for a wide range of terrestrial and aquatic species, as well as a support to tourism and their significant cultural and social values.

A sampling programme to quantify the carbon stocks in these Blue Carbon ecosystems in Abu Dhabi was designed by four members of the International Blue Carbon Scientific Working Group, a network of scientists with specialist knowledge of carbon cycling in coastal ecosystems, in conjunction with Environment Agency – Abu Dhabi (EAD) scientists. Standard field and analytical approaches were used to enable comparison with a growing global dataset on carbon stocks within coastal ecosystems. This was undertaken with local scientists with the aim of building local capacity for the future monitoring and management of the data. Forty seven sites were sampled across the Emirate that included natural mangroves, planted mangroves, salt marshes, seagrass meadows, and algal mats. Their total carbon stock, including that stored in the biomass (above-ground) and in the associated sediment (below-ground) was determined.

Carbon stocks in arid regions are generally considered to be minimal. The presence of carbon stocks within these ecosystems therefore represents a significant finding for both Abu Dhabi and region. Compared to the global database – largely derived from wet tropical and temperate systems – Blue Carbon ecosystems in Abu Dhabi do however hold less than the average carbon per unit area. Therefore, it is recommended that, from a holistic perspective, carbon sequestration be considered as one of a number of ecosystem services in Abu Dhabi. Due to their wide extent within marine waters, seagrass meadows were found to hold the greatest stock of total carbon within blue carbon ecosystems in Abu Dhabi, therefore reinforcing the importance of Marine Protected Areas in Abu Dhabi, and that of water quality.

Natural mangroves also were shown to sequester relatively more carbon than planted mangroves, particularly in the above-ground biomass, although planted mangroves can build carbon stocks on the order of decades. Conserving existing coastal ecosystems therefore is considered the most effective mechanism for managing carbon stocks, which accumulated slowly over past centuries but potentially are released rapidly if disturbed. Planting mangroves in locations that do not disturb existing carbon stocks can complement conservation measures, increasing carbon sequestration.

Summary for Scientists

A total of 47 sites were sampled across coastal Abu Dhabi (8 mature, natural mangroves; 7 planted mangrove aged 3-15 years; 5 salt marshes; 5 intertidal coastal sabkha; 4 algal flats; and 18 seagrass meadows), with replication at each site. Sampling locations were selected to include the range of environment settings along the Abu Dhabi coast, from sheltered settings to offshore islands and in shallow and deep water for seagrass.

Replicate plots along transects were assessed for plant cover and sampled for above-ground biomass and soil carbon stocks (total, organic and inorganic) to depths up to 3m depending on the substrate. At intertidal sites, additional data were collected to inform a mechanistic understanding of carbon cycling including water table depth, pore-water chemistry, root zone redox potential, and soil respiration. High resolution location and elevation data were collected via Kinematic GPS and mobile base station.

In the laboratory, above- and below-ground carbon stocks were calculated for *Avicennia marina* mangroves via previously-created allometric equations. Novel allometric equations were developed for the salt marsh species *Arthrocnemum macrostachyum*. Carbon and nitrogen analyses were performed by an elemental analyzer.

Comparing the top meter of soil across sites, carbon stocks ranged from a low of 1.9 Mg ha^{-1} (sediments beneath seagrass meadows) to a high of 164 Mg ha^{-1} (salt marsh); the means of soil carbon density across all ecosystems displayed a narrow range of 80.4 – 102.3 Mg ha^{-1}. This reflected the potential of all intertidal ecosystems to sequester carbon in dominantly carbon-poor sediments. Older natural stands of mangroves occasionally possessed an organic surface horizon up to 15cm thick, located above less organic muds, low organic sands, or bed rock material. One marsh had a buried organic horizon of former algal or mangrove soils, and some historic algal flats were covered by a relatively deep (20-30 cm) organic surface above marine sands. Deposits of seagrass beds below sabkha deposits as described in the literature were not encountered during this study.

Planted mangroves had soil carbon content that ranged from 51-155 Mg ha^{-1}, a range comparable to that of natural mangroves: 37-154 Mg ha^{-1}**.** The highest carbon stocks among planted mangrove were sites located in the Eastern Mangrove area, reflecting the relatively organic-rich soil parent material of the area. Lower carbon values were found beneath plantations at Abu Al Abyad as a consequence of a combination of factors, including the low carbon-bearing substrate (graded sabkha), the low elevation of the created soil surface within the tidal frame, and their young age.

Natural mangroves held significantly more carbon in above-ground biomass (9.3 – 91 Mg ha^{-1}) than salt marshes (1 – 4 Mg ha^{-1}) and planted mangrove (0.02 – 5 Mg ha^{-1}). Considering total biomass carbon, which includes the roots as well as above-ground living biomass, carbon stocks in natural mangroves ranged from 7 to 122 Mg ha^{-1}, and between 0.04 and 6.5 Mg ha^{-1} for planted mangroves. Significantly larger plant carbon stocks in natural mangroves versus planted mangroves reflect the slow growth rate of *A. marina* in this arid environment.

Carbon stocks of seagrass beds were low on an area basis compared to other Blue Carbon ecosystems (range 1.9 – 109 Mg ha^{-1}, mean 49.1 Mg ha^{-1}), but high in the Emirate-wide inventory because of the significantly greater coverage of meadows (mapped only to 3m depth but observed to at least 14m depth). Thus, this ecosystem holds the largest stock of carbon in the region.

Compared with other dominantly non-arid regions of the world, carbon stocks per unit area in Abu Dhabi are at the low end of the range. Typical ranges for global soil carbon stock are 102-407 Mg ha^{-1} (mangrove), 74-259 Mg ha^{-1} (salt marsh) and 26-144 Mg ha^{-1} (seagrass). However, Abu Dhabi does possess extensive areas of seagrass where carbon is being sequestered, and algal flats that are recognized for the first time in this study as being a Blue Carbon ecosystem unique to arid environments.

Coastal sabkha is not recognized as a Blue Carbon ecosystem because it is not a true marine environment. However, these systems do store buried organic soil layers that likely were derived from former Blue Carbon ecosystems.

Recommended Next Steps

This project ultimately has made significant contributions to the understanding of the science behind Blue Carbon. This has been achieved particularly for ecosystems in Abu Dhabi; however, these findings are also important at a regional and international level. Additional activities to further build upon this may include:

1. Establish a Regional Blue Carbon Working Group to further build capacity for ecosystem assessments within the Emirate and neighbouring countries and to support policy development. The working group would be a valuable addition to a growing global network for scientists and managers connected through the Blue Carbon Initiative and other international programs.

2. Continued mapping of coastal ecosystems to inform future carbon stock assessment, and conservation and restoration measures. Particular data gaps include mapping of the extent of seagrass below 3m water depth, and distribution of “thin” and “thick” deposits of algal mats along the shore;

3. Expand the regional carbon database by quantifying carbon stocks in Blue Carbon ecosystems of northern Emirates, as well as location of plantations of age greater than 15 years;

4. Enhance the planning of ecosystem restoration projects and their potential response to sea level rise through improved mapping of intertidal ecosystems by integrating coastal elevation surveys;

5. Support the planning and implementation of coastal activities, including restoration of mangrove and other Blue Carbon ecosystems by establishing a network of tidal monitoring stations;

6. Provide a means for the development of best practice criteria by monitoring and reporting restoration projects as well as the creation of Blue Carbon ecosystems;

7. Facilitate the potential for large-scale restoration by developing best practice guidelines for scaling up from small scale mangrove planting projects;

8. Excavation into coastal soils has the potential to release historically accumulated carbon stocks. Determination of these emissions would inform environmental impact assessment of these activities in coastal areas.

1 Introduction

1.1 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 part of this project is cyanobacterial "blue-green algal" mats. This study is the first to investigate algal mats as a potential Blue Carbon ecosystem. A small set of samples were also collected from coastal sabkha. When these ecosystems are destroyed, buried carbon can be released into the atmosphere, 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 significant cultural and social values.

The Abu Dhabi Blue Carbon Demonstration Project aims to improve our understanding of carbon sequestration and the other services that coastal and marine Blue Carbon ecosystems provide in the Emirate and in addition, contribute to the improved understanding of this relatively new concept on a regional and international level. The project will enhance local capacity to measure and monitor carbon in coastal ecosystems and to manage associated data. The project also identifies options for the incorporation of these values into policy and management and lead to sustainable ecosystem use and the preservation of their services for future generations.

1.2. 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 Environment Agency – Abu Dhabi (EAD) are a partner. This project provides a carbon stock inventory for intertidal and subtidal natural Blue Carbon ecosystems, as well as planted mangroves, in an arid region, reducing gaps in the global database. Recognition of algal flats as a Blue Carbon ecosystem emphasizes the importance of understanding coastal carbon cycling in arid regions of the world. The project also has helped develop Blue Carbon science and data management through the production of tools and the

[1] http://thebluecarboninitiative.org/

testing of methodologies that can be utilized and up-scaled to the international arena to enhance international Blue Carbon cooperation and training.

1.3. Project Setting

In just over 40 years, Abu Dhabi has evolved from a small fishing community to the largest of the seven Emirates of the UAE. With the vision and direction from His Highness the late Sheikh Zayed Bin Sultan Al Nahyan, the environment has become an intrinsic part of the heritage and traditions of the people of the UAE. This national affinity to the sea has led to the initiation of the Abu Dhabi Blue Carbon Demonstration project in order to explore the values which coastal ecosystems provide the UAE, and to help preserve our environmental and cultural heritage. The project, commissioned by the Abu Dhabi Global Environmental Data Initiative (AGEDI) on behalf of EAD will run until the end of 2013.

1.4. Project Structure

The project is comprised of five components:

1) A **carbon baseline assessment** that has quantified the stocks of carbon for coastal ecosystems, and rate of carbon sequestration associated with mangrove afforestation (subject of this report);
2) A **geographic assessment** that has mapped Abu Dhabi's Blue Carbon ecosystems and provides a carbon analysis tool to support informed decision making;
3) An **ecosystem services assessment** that investigated the goods and services beyond carbon sequestration that Blue Carbon ecosystems provide Abu Dhabi;
4) A **policy component** that identifies the most suitable options for incorporating Blue Carbon and Ecosystem Services in Abu Dhabi's policy and governance frameworks; and
5) A **Blue Carbon and ecosystem services finance feasibility assessment** that recommends the most feasible policy and market options for implementing Blue Carbon projects in Abu Dhabi.

1.5. Science Team

The Principal investigators of this study are members of the International Blue Carbon Scientific Working Group[2]. The goals of this voluntary network are to:

1) Assess the feasibility of coastal Blue Carbon as a conservation and management tool and its potential for climate change mitigation;

[2] 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.

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 an independent consultant, as well as Climate Change Program Manager at Environmental Science 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 Conservation category under the Verified Carbon Standards (VCS) Registry. He is working with Restore America's Estuaries to establish a global VCS wetlands restoration carbon offset methodology, and the United Nations Environment Programme (UNEP) to develop best practice guidelines for coastal wetlands carbon projects.

Dr. Patrick Megonigal is a Senior Scientist at the Smithsonian Environmental Research Centre, USA, and principal investigator of the Smithsonian Global Change Research Wetland. His major research interests concern wetland ecosystems, with an emphasis on the impacts of global change on carbon cycling. Dr. Megonigal was President of the Society of Wetland Scientists in 2007. His work includes membership on the US National Blue Ribbon Panel on Wetland Carbon Offsets, International Blue Carbon Scientific Working Group, the Restore America's Estuaries Working Group on Blue Carbon Offsets, and advising the State of Louisiana on Blue Carbon Offsets.

Dr. Boone Kauffman is a professor of Ecosystem Studies in the Department of Fisheries and Wildlife at Oregon State University and a Senior Associate with the Centre for International Forestry Research. He is a member of the IPCC, the International Blue Carbon Science and Policy Working groups, and is a science advisor to the Coalition for Rainforest Nations. Dr. Kauffman's research focus is on the relationships between land use, climate change, and carbon dynamics of tropical wetland ecosystems.

Dr. James Fourqurean is a Professor of Biological Sciences and the Director of the Marine Research and Education Initiative for the Florida Keys at Florida International University (FIU) in Miami, Florida, USA. He is a marine and estuarine ecologist with a special interest in benthic plant communities, food webs, and nutrient biogeochemistry. He is an expert in carbon storage and fluxes in coastal ecosystems, and the importance of these ecosystems to climate regulation and mitigation. In this role, he serves on both the Science and Policy Working Groups of the International Blue Carbon Initiative.

The team is supported by Dr. Lisa Schile, Post-Doctoral Research Fellow at the Smithsonian Institution's Environmental Research Centre. Topographic survey support was provided by Mr. James Kulpa of Environmental Data Solutions. Seagrass survey was supported by Dr Justin Campbell, Dr Elizabeth Lacey, and Ms Rachel Decker of Florida International University. Prepared soil samples were analyzed at the Plant Tissue and Soil Analysis Laboratory, Florida International University.

1.6. Capacity Building

During the course of this project, training on field Blue Carbon stock assessment and all necessary equipment has been provided to staff in EAD's Marine Division of the Terrestrial and Marine Biodiversity Sector. Calculation of living biomass carbon stocks can be derived from allometric and other equations provided in this report. Soil carbon stocks were derived by laboratory analysis at home institutes in the United States. Detailed description of field and analytical approaches for Blue Carbon assessments are under development by the International Blue Carbon Scientific Working Group, and a subsequent document by AGEDI will illustrate UAE specific consideration for sampling and analysis.

More broadly, awareness has been built within location agencies on existence of Blue Carbon issues. An essential component of the fieldwork was the local and international capacity building that it facilitated. During the surveys, EAD personnel and volunteers from Zayed University, Abu Dhabi National Oil Company, The Higher Colleges for Technology, Takatoff, Al Mahara Diving Company as well as the Abu Dhabi community were able to interact directly with the team of world renowned and respected coastal carbon scientists. International partners from Indonesia (Blue Ventures) and Madagascar (Ministry of Marine Affairs and Fisheries) who are currently undertaking similar projects in their own countries using the methodologies written by these scientists were also invited to participate and as a result both parties were given the opportunity to discuss the theory and practical application of carbon assessments in blue carbon ecosystems.

1.7. Report Organisation

This report summarizes findings of the field of Blue Carbon ecosystem carbon stocks for the coast of Abu Dhabi. Additionally, this report provides a summary of the local and global context of Blue Carbon research, and details methods, laboratory analysis and results of research.

1.8. Acknowledgements

This *Baseline Assessment Report for Carbon in all Ecosystems* has been prepared in response to the strategic leadership of H.E. Razan Khalifa Al Mubarak, Secretary General of Environment Agency – Abu Dhabi (EAD) and Dr. Fred Launay, Senior Advisor to the Secretary General and AGEDI Acting Director.

The EAD's Terrestrial and Marine Biodiversity Sector Marine Division, in particular Edwin Grandcourt, Himansu Das, Ibrahim Bulga, Ahmed Alanzi, Maitha Al Hameli, Hada Al Mahairbi and Mohammed Al Ali, and AGEDI's Ms. Jane Glavan, Ms. Huda Petra Shamayleh, and Ms. Larissa Owen provided expertise, local knowledge, participation in the field, and commitment to Abu Dhabi's Blue Carbon Ecosystems. We are grateful for logistical management from GRID-Arendal's Robert Barnes, Christian Neumann and Emma Corbett, who together ensured that these assessments were possible. Particular thanks is also extended to project stakeholders and field volunteers from organisations including: Zayed University; Abu Dhabi National Oil Company; The Higher Colleges for Technology; Takatoff; Al Mahara Diving Company, as well as the Abu Dhabi community and International partners Ms. Restu Nur A Fiati, and Ms. Terry Lousie Kepel from Blue Carbon Indonesia and Lalao Aigrette and Trevor Jones from Blue Ventures Madagascar.

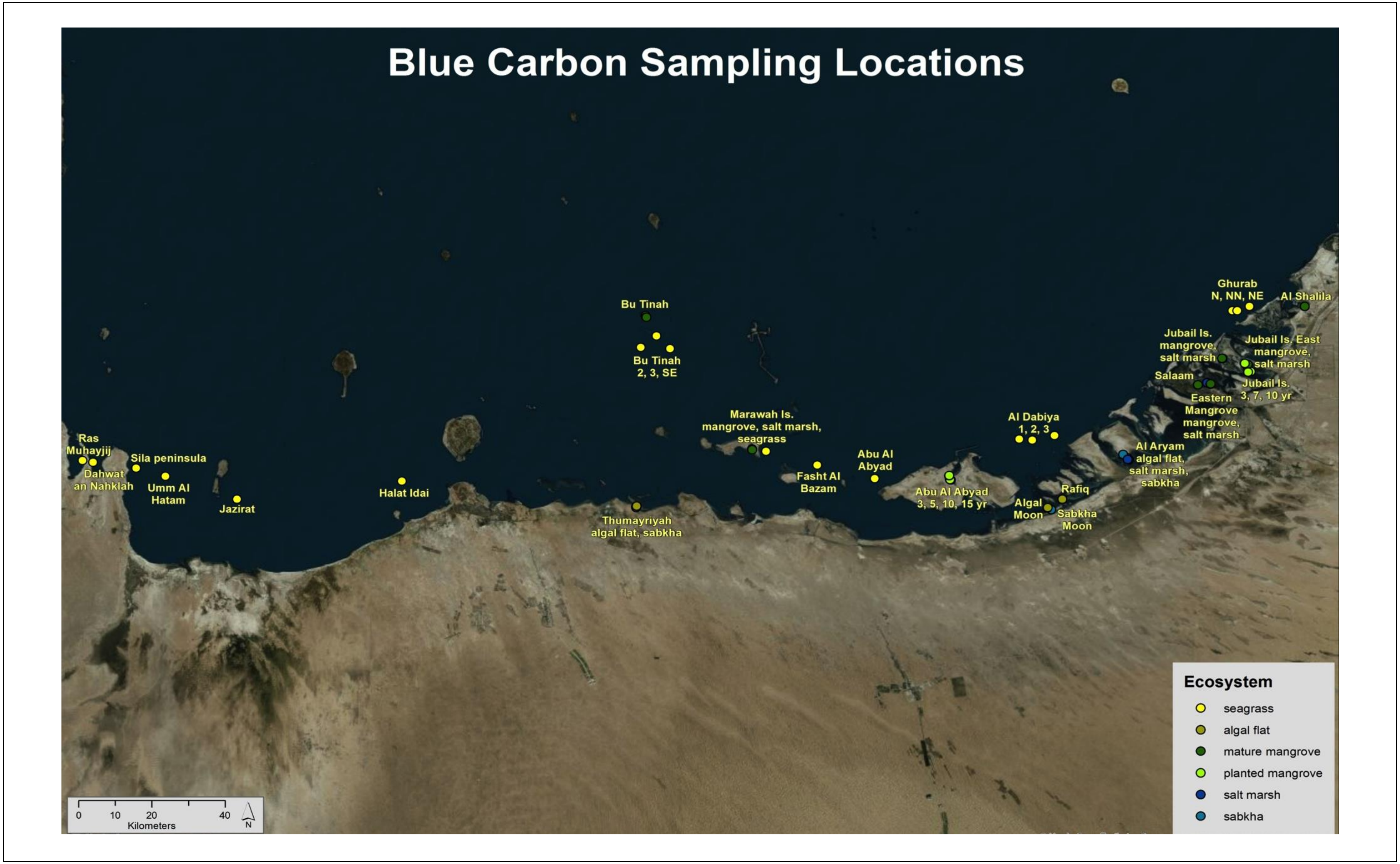
2 Study Area

2.1 Environmental Setting

The study area covered the coastal and near shore ecosystems of Abu Dhabi Emirate, between 24.12°to 24.64°N and 51.46°E to 54.66°E (Figure 1). The Emirate coast consists of a gradually sloping plain dipping into the Arabian Gulf. The coastal sabkha (salt flat) is punctuated by isolated jebels (rock out crops and hills). Numerous near shore islands and sheltered lagoons line the coast, which grades seaward into an expansive area of shallow water less than 20 m deep (Evans and Kirkham, 2002; Al-Sharhan and Kendall, 2003).

Air temperatures range from highs of over 50°C in summer to as low as 12°C in winter (EAD, 2007). Average rainfall is less than 100 mm, much less than evaporation rates of 1,000-2,000 mm. Water temperatures at the margins of the Arabian Gulf also range considerably, from as low as 10°C in winter to as high as 36°C in August. Salinity in the Arabian Gulf particularly along the southern embayments and lagoons of the Emirate of Abu Dhabi is relatively high, due to a combination of restricted exchange and high rates of evaporation, attaining over 70 PSU (practical salinity unit) in some shallow waters. There are no significant freshwater flows to the Emirate coast, though urban water outflows represent localized regions of lowered water salinity. Tides are complex, driven by interfering standing waves across the Arabian Gulf, resulting in a mix of diurnal and semi diurnal tides with a spring range of approximately 2.5m.

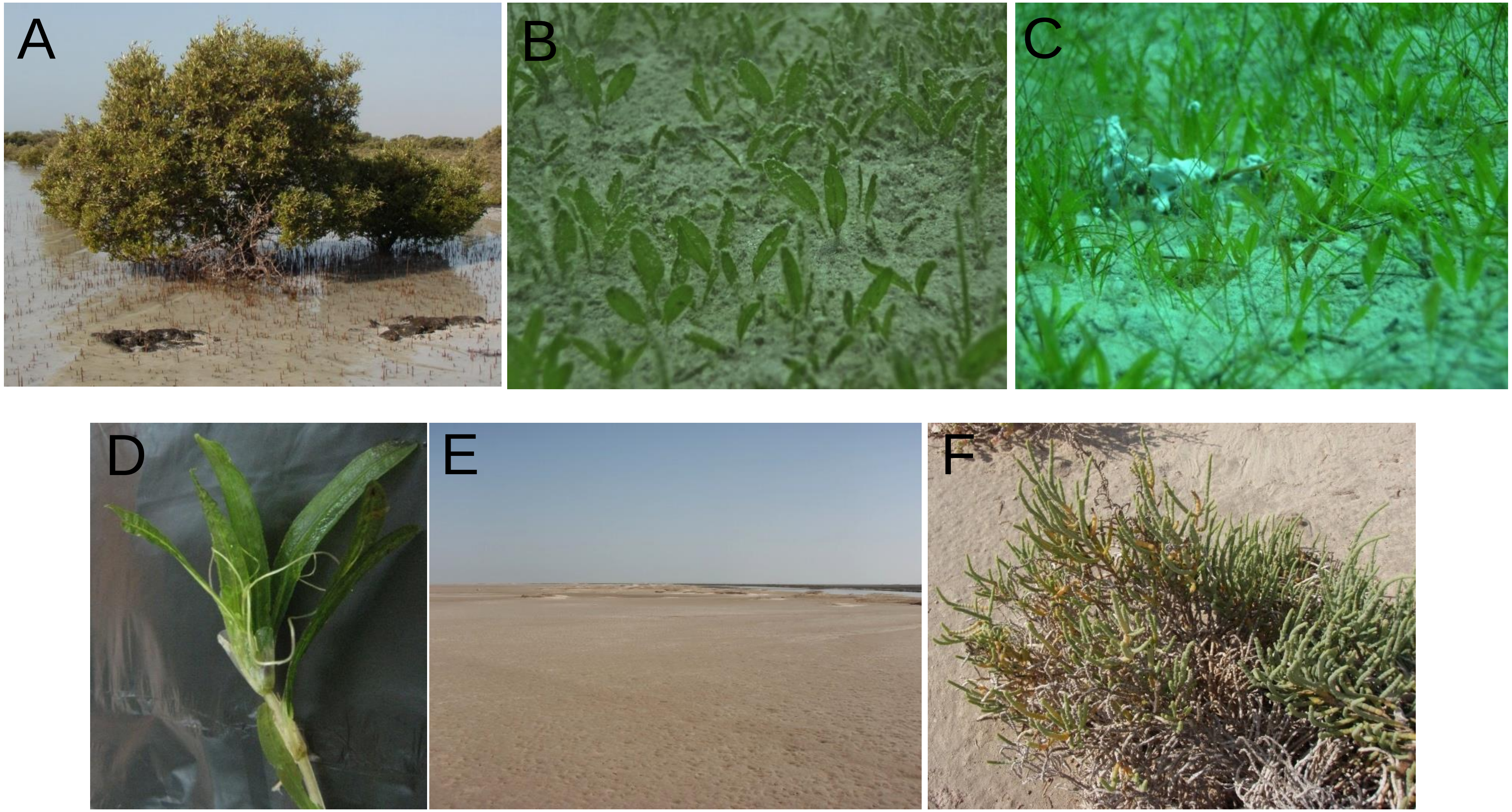
In this challenging environment the Abu Dhabi coastal plain and near shore environment supports some exceptional ecosystems. The Emirate's coastline supports one of the more northerly mangrove ecosystems, and one of the larger expanses in the Arabian Gulf, consisting naturally of a single species, *Avicennia marina* (Figure 2a). A practice of mangrove planting has been in operation in the Abu Dhabi Emirates for almost 50 years. Further, extensive seagrass meadows, distributed to depths of at least 15 meters, line much of the coastline of Abu Dhabi. These seagrass beds are vegetated with three seagrasses of tropical affinity: *Halodule uninervis*, *Halophila ovalis* and *Halophila stipulacea* (Figure 2b-d).



SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Figure 1

Locations of all intertidal and subtidal sampling locations.

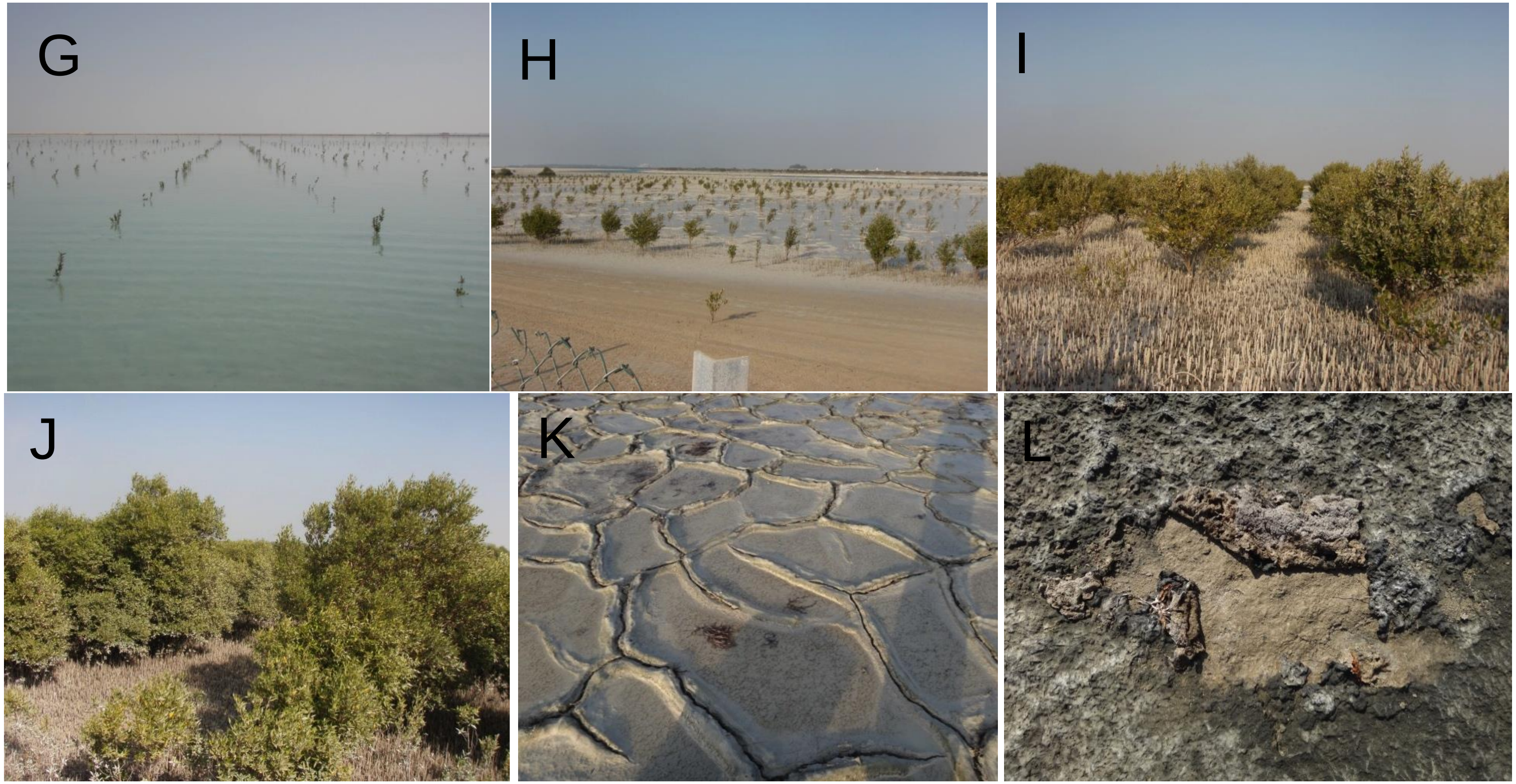


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 2A-F

Examples of a) *Avicennia marina,* b) *Halophila ovalis* c) mix of *Halodule uninervis* (thin ribbons) and *Halophila stipulacea*, d) *H. stipulacea* with female flower, e) coastal sabkha, and f) *Arthrocnemum macrostachyum*.

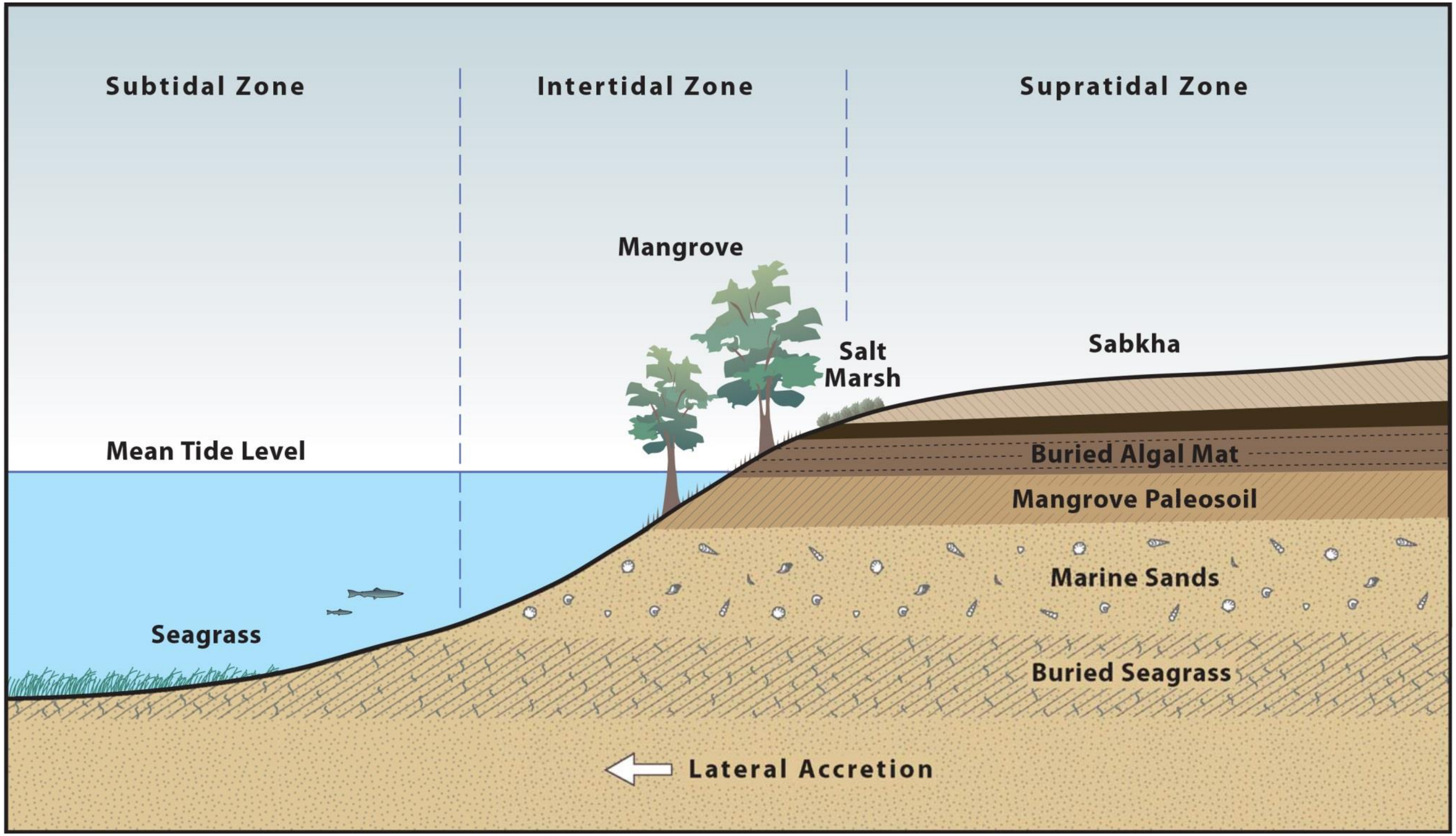


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 2G-L

Photos of g) 3 year, h) 5 year, i) 10 year, j) and 15 year old planted mangroves at Abu Al Abyad, and examples of a k) thick algal flat, and l) thin algal flat.



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 3

Diagram of blue carbon ecosystems in Abu Dhabi.

2.2 Holocene stratigraphy and relative sea level change

The geomorphology and soils of the Abu Dhabi shoreline hold a record of local, relative sea level change over the past 8000 years (Evans *et al.* 1989). Set against a global trend in sea-level rise, the position of the shore has varied in response to a balance between sea level, erosion, subsidence and sedimentation. Along the coast, relatively rapid rising sea level pushed landwards to eventually truncate aeolian dunes sands some 4 km landwards of the existing shore, marking shoreline some 4000 years ago (Evans 1964). This trend of shoreline retreat reversed at this point. Over recent millennia, during a period of relatively slow global sea-level rise, accumulating aeolian sediments combined with evaporate accumulations within coastal sabkha deposits pushed the shoreline seaward.

The history of this seaward transgression and subsequent regression is held within the soils. Sedimentological analysis describes a sequence of Pleistocene sands, overlain by deposits of microbial mats, mangrove paleosols (buried soil horizons) and seagrass beds and shelly marine sands buried beneath a reversed sequence of mangrove soils, algal mats and capped by coastal sabkha deposits (Figure 3; Kenig *et al.* 1990). Observed in channel cuttings, buried soils can be tracked over several kilometres in extent. Examples of buried mangrove soils some 25cm in thickness have been observed in Ras Ghanada, while in places more extensive buried algal mat deposits have been logged up to 55cm in thickness (Kenig *et al.* 1990). Evidence of such buried soils was observed in the present study.

2.3 Ecosystems of Interest

This study focused on quantifying carbon stocks in "traditional" Blue Carbon ecosystems of mangroves, salt marsh and seagrass meadows. In addition, algal mats and coastal sabkha were also sampled as potential Blue Carbon ecosystems. Algal mats flourish in sheltered coastal arid zone environments where vascular plants are excluded by very high soil salinities. In this region, coastal sabkha has advanced seaward for several millennia (Kendall *et al.* 2002), possibly containing past Blue Carbon sequestered by displaced algal flats, mangroves and salt marshes. The following subsections describe the ecosystems that were sampled, arranged for convenience from high to low elevation (Figure 3).

2.3.1 Coastal Sabkha

The Emirate is recognized as hosting the world's largest coastal sabkha, 300 km long and extending in places more than 20km inland (Evans and Kirkham, 2002). This 'coastal sabkha' (Figure 2e) comprises the seaward part of the sabkha, and mostly is not flooded by normal astronomical tides but is flooded several times per year when exceptionally strong Shamal winds drive seawater inland. The seaward margin of the coastal sabkha dips into the intertidal environment and intermingles with patches of vegetated coastal ecosystems. The coastal sabkha is largely devoid of vascular vegetation because of hypersalinity and long periods of dry conditions

(Kendall et al, 2002). Coastal sabkha ecosystems were broken further into low and high classifications based on distance from water bodies and perceived differences in elevation.

2.3.2 Salt marshes

Salt marshes are relatively limited in extent, occurring in patches along the fringe of sabkha, locally on sand veneers, adjacent to channels within sabkha, and amongst higher intertidal areas of mangrove stands. The salt marshes are dominated by the succulent, halophytic shrub *Arthrocnemum macrostachyum* (Figure 2f) and subdominant species *Halocnemum strobilaceum*, *Halopeplis perfoliata*, *Suaeda vermiculata*, *Salicornia europaea*, *Limonium axillare*, *Anabasis setifera* and *Salsola* spp. These species are typical of high salinity conditions and dryer, more aerated wetland soils.

2.3.3 Mangroves

Mangroves are found in scattered locations throughout the Emirate, particularly around the margins of lagoons and mud banks behind the barrier islands near Abu Dhabi island and on the outer islands. Mangroves are also found in the northern Emirates at Umm Al Quwain, Ras al Khaimah, and on the Gulf of Oman in Khor Kalba. *Avicennia marina* is the only native mangrove species (Embabi 1993), though *Rhizophoraceae* was identified in charcoal fragments dating back to between 2500 and 4000 years ago (Environmental Agency, 2006).

Recognizing the importance of mangroves, His Highness the late Sheikh Zayed Bin Sultan Al Nahyan initiated a programme of mangrove planting to maintain and expand these forests (Figure 2g-j). Mangrove planting has been on-going since the mid 1960's in the Eastern Mangrove region, and more recently at Abu Al Abyad. This includes revegetation along abandoned channels and degraded sites formerly occupied by mangroves. In addition, expansive engineering works involving excavation of coastal sabkha and algal flats for the purpose of mangrove planting are on-going on the mainland areas landward of Abu Al Abyad. Within this study both naturally-occurring and planted mangrove plantations have been assessed, the latter including a quantification of carbon stocks within a chronosequence of planted mangroves across two different sites.

2.3.4 Algal Mat

Along tidal margins of coastal sabkha where soils are consistently moist, algal mats (scientifically known as cyanobactieral mats and microbial mats) are formed by accumulation of cyanobacteria, regionally dominated by *Microcoleus chthonoplastes* (Figure 2cd). Cyanobacteria overlay laminae of bacteria, filamentous bacteria (salmon pink) and sulphur purple bacteria (purple-pink) (Kinsman and Park, 1976; Cardoso *et al., 1978*). In sheltered locations, these organisms may form a thick 'leather-like' and moist mat (Figure 2k), with a laminated fabric centimetres to tens of centimetres in thickness, and can express different surface morphologies depending on location (Kendall and Skipwith 1968). Periodic storms bring sediments to the mats leading to layering of organic and non-organic sediment. Higher in the tidal frame where evaporation is high, and in locations subject to more regular disturbance, the algal film may only be a few millimetres in thickness, covering shelly sands (Figure 2l) (Kendall and Skipwith 1968). This study assessed the ability of these algal mats to both sequester and store carbon and, therefore, their classification as 'potential Blue Carbon ecosystems'.

2.3.5 Seagrasses

Seagrass meadows are an extensive and important ecosystem in the Arabian Gulf. There are three species in the region, *Halodule uninervis, Halophila ovalis*, *Halophila stipulacea* (Figures 2 b-d). Although this represents a lower diversity compared to the eleven and seven species documented in the Red and Arabian Seas, respectively (Phillips 2003; Lipkin *et al.* 2003), the extent of this habitat is significant. Whereas only limited seagrass coverage is found in Kuwait and Iran, expansive areas of seagrass meadows are located between Qatar and the UAE. Within Abu Dhabi, an expansive complex of seagrass meadows extends around the islands and along the nearshore coastal plain. In sheltered locations these meadows intermingle with algal beds (*Hormophysa*). The large size of the seagrass bed supports a commensurate population of Dugongs and green turtles.

3 Field Sampling

3.1 Location Selection Process

A priority was placed on quantifying baseline carbon stocks of existing natural intertidal ecosystems, seagrass beds, and planted mangroves, as little basic information is known of the carbon stocks in the Emirates. Intertidal sites were selected representing a range of environmental settings (e.g. islands, mainland coast line, sheltered, exposed) were located to explore relationships between environmental drivers and carbon storage. Similarly the seagrass survey examined locations varying in geomorphic contexts, shallow to deep, sheltered to exposed, and along the full extent of the Emirate coastline. In both cases, survey locations were selected in consultation with EAD staff using the following criteria: (i) sample across as much of the Abu Dhabi coast as logistically possible, (ii) sample areas where a particular ecosystem has a large spatial extent, and (iii) co-locate samples for sabkha, algal flat, marsh, and mangrove when possible. Scheduled to meet appropriate weather windows, the intertidal wetland field campaign occurred between January 15 and January 31, 2013, and the seagrass survey between April 28th and May 7th, 2013.

3.1.1 Intertidal Surveys

For the intertidal surveys, the site selection was undertaken in coordination with EAD and AGEDI staff experienced in local field conditions. The United Nations Environment Programme – World Conservation Monitoring Centre (UNEP-WCMC) staff developed and conducted ground-truthing of the Blue Carbon ecosystem map. Potential intertidal sampling locations were identified by EAD staff (Table 1) and a target number of sites to sample were identified (Table 2). Additional mangrove carbon pool measurements were collected from two time series of planted mangroves to quantify carbon stock accumulation. Although mangrove plantings have occurred over the past 50 years in Abu Dhabi, sampling was limited to sites that were all 15 years old or younger.

Table 1: Wetland sampling targets and achievement

Environment	Target	Sampled
Natural mangroves	5-10	8
Planted mangroves	5-10	7
Salt marsh	5	5
Sabkha / Algal Flat	2-5	9
Seagrass Meadows	10-18	18
Converted intertidal wetlands	1-5	0

Table 2: Age characteristics of intertidal wetland sampling opportunities

Strata	Site Name	Latitude and Longitude	
Natural Mangroves			
Eastern Abu Dhabi	Ras Ghanada 1	24° 49' 28.41'' N	54° 44' 00.65'' E
Eastern Abu Dhabi	Ras Ghanada 2	24° 46' 29.21'' N	54° 45' 32.90'' E
Central Abu Dhabi	Kite Beach	24° 31' 49.29'' N	44° 33' 31.04'' E
Central Abu Dhabi	Ras Ghurab	24° 35' 36.29'' N	54° 35' 47.87'' E
Central Abu Dhabi	Ras Ghurab (South)	24° 33' 08.84'' N	54° 34' 28.67'' E
Central Abu Dhabi	Nr. Saadiyat	24° 32' 54.88'' N	54° 30' 29.41'' E
Western Abu Dhabi	Abu al Abyad (approx.)	24° 15' 27.66'' N	53° 51' 41.89'' E
Western Abu Dhabi	Al Basm	24° 19' 12.50'' N	53° 05' 59.13'' E
Western Abu Dhabi	Al Fiyaa	24° 17' 25.12'' N	53° 12' 54.67'' E
Western Abu Dhabi	Marawah Is.	24° 18' 17.66'' N	53° 20' 31.81'' E
30-50 yr. old plantations			
Western Abu Dhabi	Bu Tinah	24° 37' 54.65'' N	53° 03' 06.21'' E
Western Abu Dhabi	Mubaraz	24° 27' 28.41'' N	53° 22' 13.93'' E
Central Abu Dhabi	Eastern Mangrove 1	24° 26 '56.40'' N	54° 26' 35.03'' E
Central Abu Dhabi	Eastern Mangrove 2	24° 27' 04.85'' N	54 °24' 32.15'' E
10-20 yr. old plantations			
Eastern Abu Dhabi	Ras Ghanada 3	24° 46' 48.34'' N	54° 45' 55.30'' E
Eastern Abu Dhabi	Ras Ghanada 4	24° 48' 29.95'' N	54° 45' 43.46'' E
Western Abu Dhabi	Al Aryam	24° 17' 36.28'' N	54° 11' 28.61'' E
2-10 yr. old plantations			
Central Abu Dhabi	Jubail East	24° 31' 04.36'' N	54° 30' 54.54'' E
Central Abu Dhabi	Jubail SE	24° 29' 07.81'' N	54° 34' 57.58'' E
Western Abu Dhabi	Abul Abyad 1	(exact coordinates TBD after site visit)	
Western Abu Dhabi	Abul Abyad 2	(exact coordinates TBD after site visit)	
Eastern Abu Dhabi	Ras Ghanada 5	(exact coordinates TBD after site visit)	

A reconnaissance of potential mangroves, salt marshes and mangrove plantation sites was undertaken to provide an initial assessment of field campaign opportunities and constraints. Abu Al Abyad and Thumayriyah were visited, where the full range of target ecosystems could be observed. Based upon the site soil characteristics, which were dominantly sandy, a robust soil corer specifically designed for wetland sampling was selected for the field campaigns.

Intertidal ecosystems (mangroves, salt marsh, coastal sabkha, and algal flats) were sampled between Thumayriyah to the west, Bu Tinah to the north, and areas surrounding Jubail Island to the east and northeast (Figure 1).

3.1.2 Subtidal Surveys

Below the Arabian Gulf waters, the extent of seagrass beds below depths of approximately 3m is unmapped, although beds were found to be widespread to depth of 14m or more. Seagrass meadows composed of the species of seagrasses that occur in the study area may be ephemeral, influenced by inter annual variability in seasonal extreme water temperatures and storm energy (Duarte *et al.* 2005). To select the sites, therefore, EAD staff provided a list of candidate sites so that sampling would occur in exposed and protected locations in a variety of water depths representing the three common seagrass species, and distributed in space along the entire coastline of Abu Dhabi. EAD staff provided these locations, informed by their history of tracking seagrass-dependent herbivores (sea turtles and dugongs), so that a majority of the sample sites were in areas of long-term interest to EAD. Eighteen sites, ranging from Ras Muhayjij in the east to Ghurab NE in the west (Table 3; Figure 4) were chosen for the analysis of carbon storage.

Table 3: Location and physical characteristics of seagrass carbon storage survey sites

Site name	Latitude (°N)	Longitude (°E)	Soil depth (cm)	Water depth (m)	Salinity (PSU)	Temperature (°C)
Ras Muhayjij	24.25277	51.66758	74.5	7.0	nd	nd
Dahwat an Nahklah	24.24782	51.69347	94.0	4.6	46.6	25.3
Sila peninsula	24.23258	51.79963	42.5	14.0	45.3	25.4
Umm Al Hatam	24.21152	51.87123	88.0	6.1	45.2	25.4
Jazirat	24.15132	52.04760	62.0	5.0	45.4	25.4
Halat Idai	24.19905	52.45295	16.5	8.9	45.1	25.4
Bu Tinah 3	24.54852	53.03997	61.5	5.2	43.4	27.4
Bu Tinah 2	24.57855	53.07900	100.0	2.7	43.6	27.4
Bu Tina SE	24.54534	53.11234	41.4	6.1	43.2	27.2
Marawah	24.27702	53.34829	59.0	6.4	44.9	26.8
Fasht al Basm	24.24085	53.47422	70.0	2.7	44.8	28.1
Abu al Abyad	24.20513	53.61585	89.0	4.6	46.3	28.3
Al Dabiya 1	24.30876	53.97083	9.5	4.6	43.8	27.8
Al Dabiya 2	24.30582	54.00273	39.0	4.0	43.8	28.0
Al Dabiya 3	24.31826	54.05725	100.0	7.9	44.6	28.1
Ghurab N	24.64473	54.495	8.5	6.1	42.5	26.2
Ghurab NN	24.64498	54.50703	39.5	6.1	42.3	25.9
Ghurab NE	24.65578	54.53673	43.0	6.1	42.7	25.0

3.2 Sampling of Intertidal Ecosystems

Sampling locations for the selected mature mangroves, salt marshes and algal flats were representative of the surrounding ecosystem in the region (Table 4). Transects typically were established where they covered the range in variation within the stands. The priority was to collect replicate samples along a transect within a uniform patch of vegetation.

Mangrove and marsh systems were identified based on plant community composition; algal flats were identified by the presence of either a dark cyanobacterial crust or thick, spongy mat; sabkha was identified by the lack of either vascular plants or a cyanobacterial mat. The distinction between high and low sabkha was based on a visual of elevation and soil surface color.

Table 4: Location and physical characteristics of intertidal habitats

Ecosystem	Site	Soil depth (cm)	Salinity (PSU)	pH	Water Table (cm)	Latitude (°N)	Longitude (°E)	elevation (m WGS84)	tidal elevation (m UKHO)
Algal Flat	Al Aryam	183	148	7.4	-25	24.254296	54.240362	-32.16	1.29
	Algal Moon	43	85	8.3		24.128746	54.040419	-32.19	1.28
	Rafiq Island	17	120		-15	24.151333	54.077128		
	Thumayriyah	50	286	7.9	-9	24.133267	53.029980		
Mangrove	Al Shalila	149	43	8.4		24.655859	54.672665	-33.01	0.89
	Bu Tinah Janoub	22	51	7.6	-24	24.627767	53.053846	-31.53	1.60
	Bu Tinah Shamal	28	55	7.2	-24	24.631651	53.051942	-31.62	1.55
	Eastern Mangrove	35	53	7.1		24.452772	54.441036	-32.62	1.08
	Jubail Island	300	49	7.4		24.519358	54.469570	-32.93	0.93
	Jubail Island East	42	57	7.3	-8	24.503426	54.532954	-32.82	0.98
	Marawah Island	26	65	7.0	-6	24.281305	53.313625	-31.89	1.42
	Salaam	189	42	7.7	-21	24.450428	54.409897	-32.55	1.11
Planted Mangrove	Abu al Abyad 3 yr	81	65		-5	24.201363	53.802275	-32.69	1.05
	Abu al Abyad 5 yr	29	75		-9	24.203231	53.800678	-32.73	1.02
	Abu al Abyad 10 yr	30	50		-13	24.203849	53.800127	-32.70	1.04
	Abu al Abyad 15 yr	29	50	7.7	-5	24.213221	53.798755		
	Eastern Mangrove 3 yr	76				24.506662	54.525570	-33.11	0.84
	Eastern Mangrove 7 yr	82		7.4		24.483953	54.533643	-32.75	1.01
	Eastern Mangrove 10 yr	100		7.3		24.485560	54.540176	-32.93	0.93
Salt marsh	Al Aryam	142	77	7.8	-45	24.255952	54.237724	-32.08	1.38
	Eastern Mangrove	141	39		-55	24.455623	54.433512	-32.55	1.14
	Jubail Island	40	42	7.6	-29	24.519518	54.471027	-32.55	1.13
	Jubail Island East	51	61	7.3	-19	24.497904	54.532473	-32.49	1.17
	Marawah Island	19				24.282382	53.313589	-31.67	1.59
Low Sabkha	Al Aryam	38				24.259940	54.236206	-31.88	1.43
	Sabkha Moon	41				24.123775	54.049549	-31.72	1.50
	Thumayriyah	56	250	7.2	-27	24.132747	53.029166		
High Sabkha	Al Aryam	39				24.268135	54.226300	-31.76	1.49
	Thumayriyah	47				24.130094	53.029041		

SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Abu Dhabi Blue Carbon Project

Figure 4

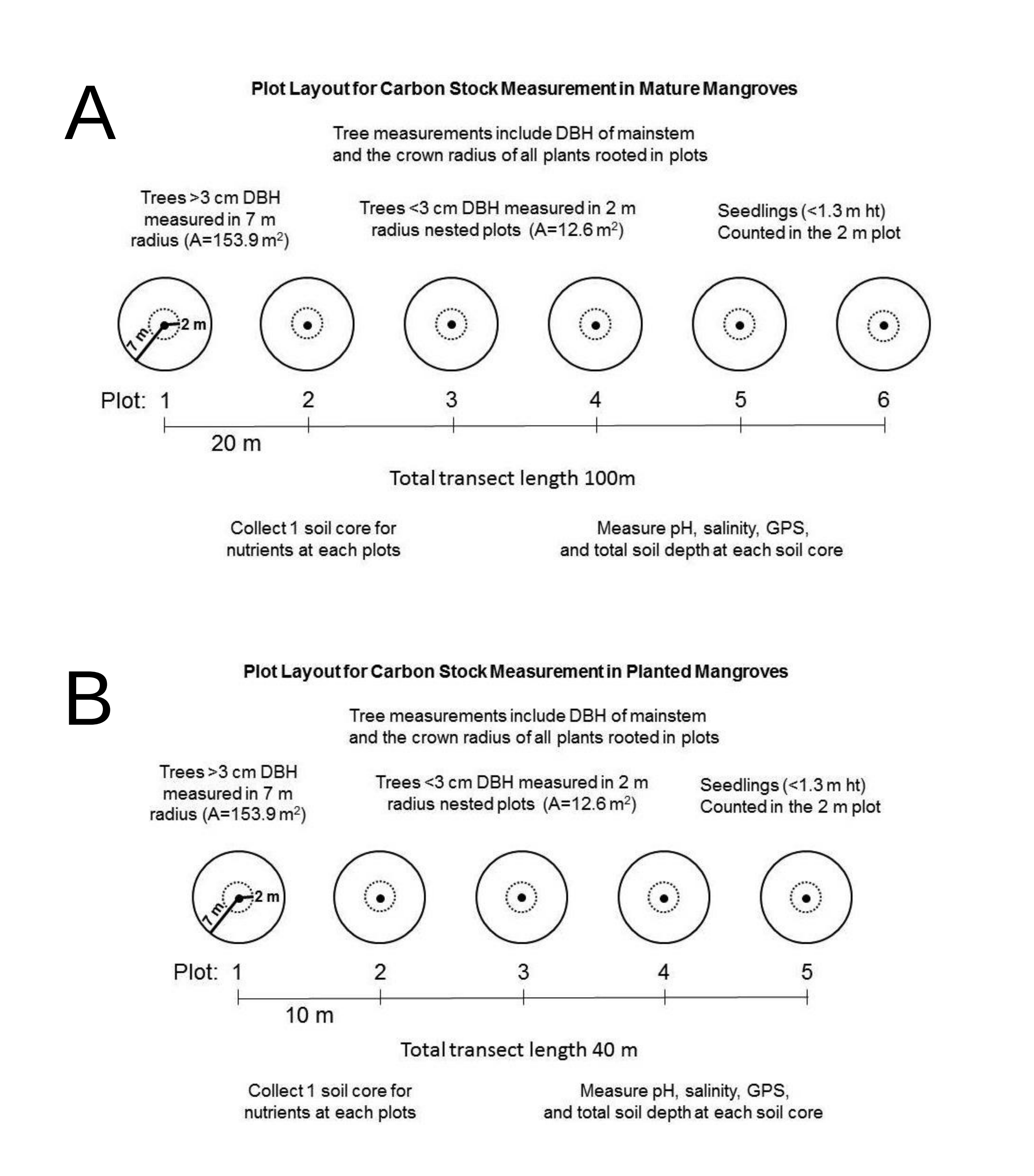
Site locations of sampled seagrass meadows.

SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Abu Dhabi Blue Carbon Project

Figure 5

Site locations of sampled mature and planted mangrove forests.



SOURCE: Kauffman and Donato 2012; Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 6

Experimental field design to determine forest structure and carbon stocks in a) mature and b) planted mangroves.

3.2.1 Mangroves

Eight natural mangrove stands and seven planted stands were sampled across the Abu Dhabi coastline (Figure 5). The latter included three sites aged 3, 7, and 10 years that were sampled on Jubail Island near the city of Abu Dhabi and four adjacent sites aged 3, 7, 10, and 15 years that were measured on Abu Al Abyad (Figure 2g-j).

At each site, whole-ecosystem carbon stocks were measured, including the determination of above- and below-ground carbon content. Measurements in mature mangrove forests followed a nested plot approach outlined by Kauffman and Donato (2012), with minor modifications listed below (Figure 6a). At each mangrove site, carbon stocks were measured in six 7m fixed-radius circular plots placed 20m apart along a 100m transect (Figure 6a; Appendix A, Figure 1a). A modified sampling approach was used in planted mangroves, which is described in the section below (Figure 6b). Additionally, the rates of carbon sequestration were calculated for each planted mangrove site.

This sampling methodology was modified slightly from Kauffman and Donato (2012) to match conditions found in Abu Dhabi. In order to adequately account for the prevalence of smaller trees, we sampled all mangroves greater than 3cm DBH instead of 5cm DBH in the 7m plots. Additionally, given the smaller patch size of the mangroves, the plots were established 20m apart instead of every 25m. As there was no downed wood in the plots, we did not sample for this component.

Above-ground carbon content

In each mature mangrove plot, tree density, basal area, and crown area were quantified through measurements of the crown diameter and mainstem diameter at 1.3m height (diameter at breast height - DBH) of all trees rooted within the plot (Appendix A, Figure 2a). All trees with a DBH greater than 3cm were measured within the 7m radius plot (154m^2 in area). Trees taller than 1.3m with a DBH less than 3cm were measured in a nested plot with a radius of 2m (12.56m^2 in area). Seedlings, defined as individuals less than 1.3m in height, were counted in the 2m radius plot (Appendix A, Figure 2b).

At each planted mangrove site, carbon stocks were measured in five 2m radius plots that were established 10m apart along a 40m transect (Figure 6b). In the younger stands dominated by individuals less than 1.3m in height, we measured the crown diameter and mainstem diameter at 30-50cm. In the 3, 5, and 10 year old planted mangrove sites in Abu al Abyad, trees were planted in an evenly-spaced grid; therefore, the circular plot design was not used. In this case, plant density was calculated by measuring the average plant spacing as well as the diameter and crown area of a large sample (50-100 trees) of the planted trees. The data were applied to published allometric equations (Table 5) to calculate above- and below-ground mangrove biomass. This is discussed further in Section 4.1.1

Below-ground carbon content

At all mangrove plots, soil samples for dry bulk density (DBD) and nutrient concentration, specifically carbon and nitrogen, were collected using a peat auger consisting of a semi-cylindrical chamber of 5.1cm radius attached to a cross handle (Appendix A, Figure 1 b, c). This auger was efficient for collecting relatively undisturbed cores from wet soils under mangroves (Donato *et al.* 2011). The core was systematically divided into depth intervals of 0-15cm, 15-30cm, 30-50cm, 50-100cm and greater than 100cm (if basement materials were not encountered before 100cm depth). In some instances, unique layers were discovered within the soil core and were sampled specifically. From each core, the depth to parent materials (marine sands or bed rock) was measured. In the approximate center of each of the depth intervals samples of a known volume (5cm in width) were collected (Appendix A, Figure 1d), placed in metal cans, and transported to the laboratory. The area of the soil auger opening was 16.88cm^2 and the total volume of the 5cm wide sample collected was 81.42cm^3.

Table 5: Allometric equations utilised to calculate plant biomass for *A. Marina* trees

	Equation	R^2	Source	Location developed
Above-ground				
Avicennia marina	$B = 0.1848D^{2.3524}$	R^2=0.98	Dharmawan and Siregar (2008)	Indonesia
	$B=0.4721D^{2.2990}$		Clough et al. 1997	Australia
	$B= 0.308D^{2.113}$	R^2=0.99	Comely and McGuiness (2005)	Australia
A. germinans (plants <4cm DBH)	$B=200.4D^{2.1}*.001$		Fromard et al. (1998)	French Guinea
Below-ground				
	$B=0.199*\rho^{0.899}*D^{2.22}$	R^2=0.95	Komiyama et al. (2005)	Global
	$B=0.1682D^{1.7939}$	R^2=0.95	Dharmawan and Siregar (2008)	Indonesia
	$B=1.28D^{.1.17}$	R^2=0.98	Comely and McGuiness (2005)	Australia
	B=0923*aboveground biomass		Below-ground/above-ground ratio based upon Comely and McGuiness (2005)	Australia

B = biomass (kg), ht = height (m), D = diameter at breast height (cm), ρ = wood density (g cm^{-3}).

3.2.2 Salt Marshes

All five of the salt marshes sampled were monospecific stands of *A. macrostachyum*, fringed at higher elevations by other succulent species and lower elevations by *A. marina* (Figure 7).

Above-ground carbon content

As with the mangrove sampling design, the salt marsh biomass sampling design was based on a single transect per site set perpendicular to the adjacent major body of water. Six plots were established along the 100m transect, spaced at 20m intervals, and the plot radius ranged from 1m to 4m, depending on the plant density at a site. Larger plot sizes were chosen when plant density was low. Within each plot, the height and two widths of the crown (taken perpendicular from each other) were measured on each plant (Appendix A, Figure 2c, d).

Since no allometric equations have been developed for *A. macrostachyum* biomass, the data necessary to develop such an equation were collated. In order to develop a relationship between plant size and biomass, the entire above-ground biomass of multiple plants (24 in total) of different sizes was harvested from Jubail Island, Eastern Mangrove, and Al Aryam. No samples of below-ground biomass were collected within these samples. Plants were placed into plastic bags and brought to a local laboratory for processing.

Below-ground carbon content

At all plots, soil samples for dry bulk density (DBD) and nutrient concentration, specifically carbon and nitrogen, were conducted as per the mangrove sampling described in Section 3.2.1.

SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Abu Dhabi Blue Carbon Project

Figure 7

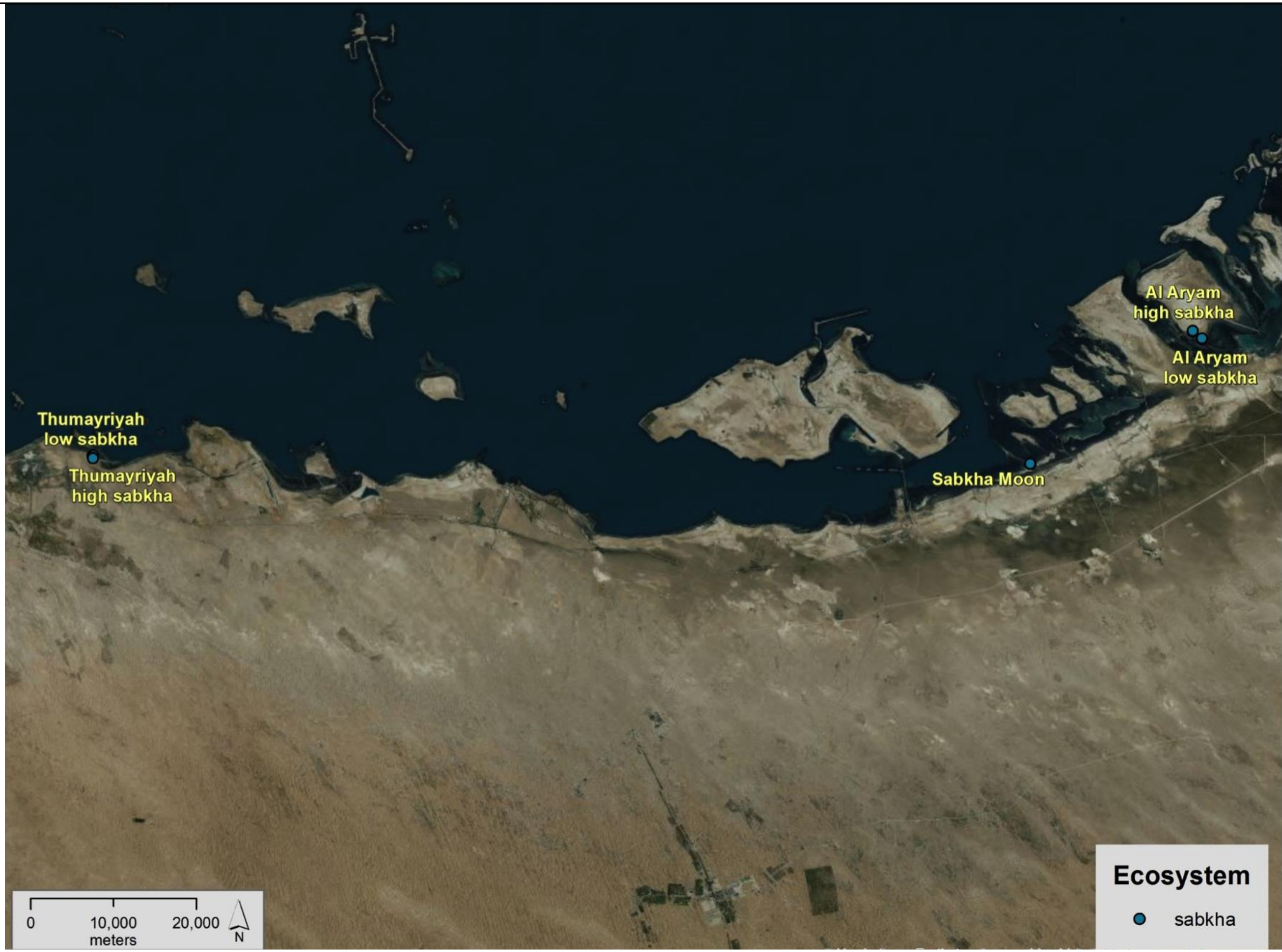
Site locations of sampled salt marshes.

SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Abu Dhabi Blue Carbon Project

Figure 8

Site locations of sampled algal flats.



SOURCE: Abu Dhabi Blue Carbon Project; Image Source: Harris Corp, Earthstar Geographics LLC, Microsoft Corporation

Abu Dhabi Blue Carbon Project

Figure 9

Site locations of coastal sabkha.

3.2.3 Algal Flats

Four algal flats were sampled across the Emirate (Figure 8). Sites ranged from thick polygonal mats to thin, flakey mats. The same below-ground carbon content soil sampling methodology was used for mangroves and salt marshes. The number of plots sampled per transect ranged from three to five plots and were spaced every 20m along a transect. At Thumayriyah, a shovel was used instead of the soil auger to collect soil samples and the volume of each soil sample collected was recorded. Due to the lack of emergent vegetation in this ecosystem, no above-ground biomass samples were collected.

3.2.4 Coastal Sabkha

Five coastal sabkha were sampled across the Emirate (Figure 9). The same soil sampling methodology was used to sample coastal sabkha as was used for the other ecosystems; three to five plots were sampled every 20m along a transect. At Thumayriyah, a shovel was used instead of the peat auger to collect soil samples and the volume of each soil sample collected was recorded. Due to the lack of emergent vegetation, no biomass samples were collected.

3.3 Seagrasses

At each candidate seagrass survey location (Figure 4), the presence of seagrass was confirmed with a drop camera. If seagrass was present, boats were anchored. Water temperature and salinity data, as well as geographic location and water depth were recorded. Dive teams entered the water to accomplish three tasks: assess seagrass cover along a 50m transect; collect a shallow, large-diameter sediment core for quantifying seagrass biomass (to determine total plant carbon content); and collect deeper sediment cores to measure soil properties (to determine soil carbon content) at the site.

Above-ground carbon content

Seagrass cover and species composition were recorded along a 50m transect extending from the boat anchor. At 10 distances along the transect that were determined by using a random number table, a 0.25m^2 quadrat was placed on the sediment surface. All conspicuous benthic taxa in each quadrat were recorded and given a cover score using a modified Braun-Blanquet scale (Table 6; Fourqurean *et al.* 2001). The Bran-Blanquet cover scores were subsequently converted to % cover. Additionally, one oblique photograph was taken of each quadrat.

Seagrass biomass was collected with a 15cm core tube inserted 40cm into the sediment. The cores were pulled and the contents washed through a coarse mesh bag to separate the plant material from the soil. These biomass samples were separated by species. *Halodule uninervis* samples were further separated into above- and below-ground components to allow comparison with other measures of abundance of this species throughout its global distribution.

Below-ground carbon content

During the field campaign, 40 soil cores were collected from 18 distinct seagrass meadows. Soil cores were collected (in duplicate at most sites, in triplicate at a few sites) by driving a diver-operated piston core into the soils until a depth of 1m or refusal was reached. The corer was designed robustly and made from steel so as to allow it to be driven into hard substrata if needed. These cores were returned to the boat, where they were subsampled at 3 cm to 9 cm intervals for the determination of dry bulk density, loss on ignition, and organic carbon content. These subsamples were 5.0 cm^3 subcores collected with a corer fashioned from a cut-off 20 cm^3 syringe, taken through sampling ports drilled into the larger piston core tubes. Each 5.0 cm^3 soil subsample was captured in a pre-weighed polyethelene 20mL scintillation vial in the field and returned to the laboratory for processing.

3.4 In Situ Data Collection

In addition to the above- and below-ground carbon content assessment for each of the Blue Carbon ecosystems and potential Blue Carbon ecosystems, additional measurements were taken to:

- Accurately record the general and relative elevation of Blue Carbon and potential Blue Carbon ecosystems;
- Provide additional insight into anaerobic microbial processes that influence soil carbon cycling rates by measuring soil pore-water chemistry and redox potential; and
- Measure soil respiration to document loss of CO_2 from the system by microbial activity.

3.4.1 Elevation data

Real-Time Kinematic GPS (RTK-GPS) in conjunction with static survey techniques was utilized in order to collect high-accuracy position and elevation data at each field site. Each field survey consisted of two components: 1) establishing a GPS base station point which comprised of a survey grade (± 0.03 m) position and elevation, and 2) collecting position and elevation data along each transect. The field surveys utilized a *Leica System 1200* GPS system configured with hardware and software that enabled the use of the Russian Global Navigation Satellite System (GLONASS) satellite network (in addition to the U.S. GPS constellation). Utilization of GLONASS-enabled receivers increased the number of available satellites to an average of 15 – 20, thus enabling survey-grade accuracy within riparian vegetation. In order to establish a survey-grade point at each location, a static survey was performed on a temporary benchmark established at each site (Appendix A, Figure 3a). Static GPS surveys allow various systematic errors to be resolved when high accuracy vertical and horizontal positioning is required. At least 4 hours of static GPS base station data needed to be collected at each site. During static data collection, elevation transect data were collected using the GPS rover in RTK mode. In addition to surveying plot transects, water surface elevation was surveyed at least once at each site in order to relate surveyed elevations to tidal elevations (Appendix A, Figure 3b).

3.4.2 Pore-water chemistry

A variety of measurements related to the microbial carbon cycling and plant growth were made on most transects, including redox potential and chemical analysis of pore-water. Redox potential was estimated from five replicate platinum-tipped electrodes inserted 10 cm deep into the soil for a period of at least one minute (Appendix A, Figure 4a). Potential was measured with a high-impedance volt meter and corrected for the potential of the calomel reference electrode by adding 244 mV. Since the electrodes equilibrated for less than 10 minutes before reading, redox potentials reported here are likely to be higher than potentials measured after 24 hours of equilibration (Megonigal and Rabenhorst, in press). For this reason a redox potential value below which the soils can be considered anaerobic was not chosen. Differences among sites are therefore considered to be indicative of the relative rank in soil oxygen availability.

Chemical analysis of pore-water provides additional insight into anaerobic microbial processes that influence soil carbon cycling. On sites that were wet enough to have a shallow water table, soil pore-water was collected from the boreholes created by soil coring. Water was extracted from 5-10 cm below the soil surface with a syringe, either directly or through a Teflon straw. Methane was extracted by shaking a 1:1 volume ratio of porewater and ambient air for 60 seconds, then expelling the water. The resulting air sample was injected into an evacuated Exetainer vial, and shipped to the United States for analysis. A second sample of pore-water was filtered through a 0.20 µm filter to remove microorganisms, shipped to the United States, and analysed for sulphate and chloride concentration. These data were used to calculate the sulphate depletion ratio:

(*Equation 1*) **Sulphate Depletion = ([Cl] x [Rsw]-1) – [SO_4]**

Where [Cl] and [SO_4] are the concentration of these elements in pore-water and Rsw is the ratio of Cl to SO_4 in surface sea water, and assumed to be 19.33 in this instance (Keller *et al.* 2009).

Salinity also was measured with a refractometer with a scale that ranged up to 160. On samples that exceeded 160 used the chloride ion concentration to calculate salinity: Salinity = 0.030 + 1.8050 x chlorinity. Pore-water pH was measured with a portable pH electrode.

3.4.3 Soil Respiration

Although the primary goal of the survey was to quantify wetland soil and plant carbon stocks, carbon dioxide gas exchange rates from the soil surface also were recorded to estimate carbon loss from the soils. Carbon dioxide emissions were measured with a LICOR 6400 soil respiration analyser, which is capable of measuring respiration rates in a period of five minutes or less on a small spatial scale (Appendix A, Figure 4b). Anywhere from 2 to 18 soil flux measurements were taken at each site, although not all sites were measured.

3.5 Sample Preparation and Transportation

All soil and plant samples were dried in laboratories provided by EAD and placed into sealed plastic bags prior to transport back to the laboratories in the United States. Samples were placed into strong plastic bins with lids and taped for transport.

4 Laboratory and Data Analysis

4.1 Quantification of Intertidal Ecosystem Biomass

4.1.1 Mangroves

Allometric equations were used to calculate tree biomass for each site (Table 5). Several allometric equations were reviewed to determine the most appropriate for *A. marina* biomass, including: Clough *et al.* 1996; Comely and McGuiness 2005; Dharmawan and Siregar 2008; and Pavaresh *et al.* 2012. For above-ground biomass, equations developed by Clough *et al.* (1997) from the arid coast of Northwestern Australia were applied as, similar to this study, the individual mangroves were frequently multi-stemmed. In addition, this equation was developed from sites with an annual rainfall of less than 400mm, high levels of solar radiation, and day time temperatures of up to 45-50^{o}C. The prevailing environmental conditions on which this is based therefore are very similar to those in Abu Dhabi. The equation by Clough *et al.* (1997) yielded higher estimates of biomass than the equations developed in wetter regions for single stemmed tall individuals. Below-ground biomass for mangrove trees was calculated using the formula by Comely and McGuiness (2005), which was developed specifically for *A. marina*.

In the absence of an existing allometric equation for small *A. marina* trees found in the planted sites, the formula developed for small *Avicennia germinans* plants (less than 4cm DBH) by Fromard *et al.* (1998) was applied.

No existing equation for below-ground biomass for small trees was found. Comely and McGuiness (2005) reported that the total below ground biomass accounted for 48% of the total plant biomass of *A. marina*; therefore, the below-ground biomass of planted mangroves was calculated as 0.923 of that of above-ground biomass.

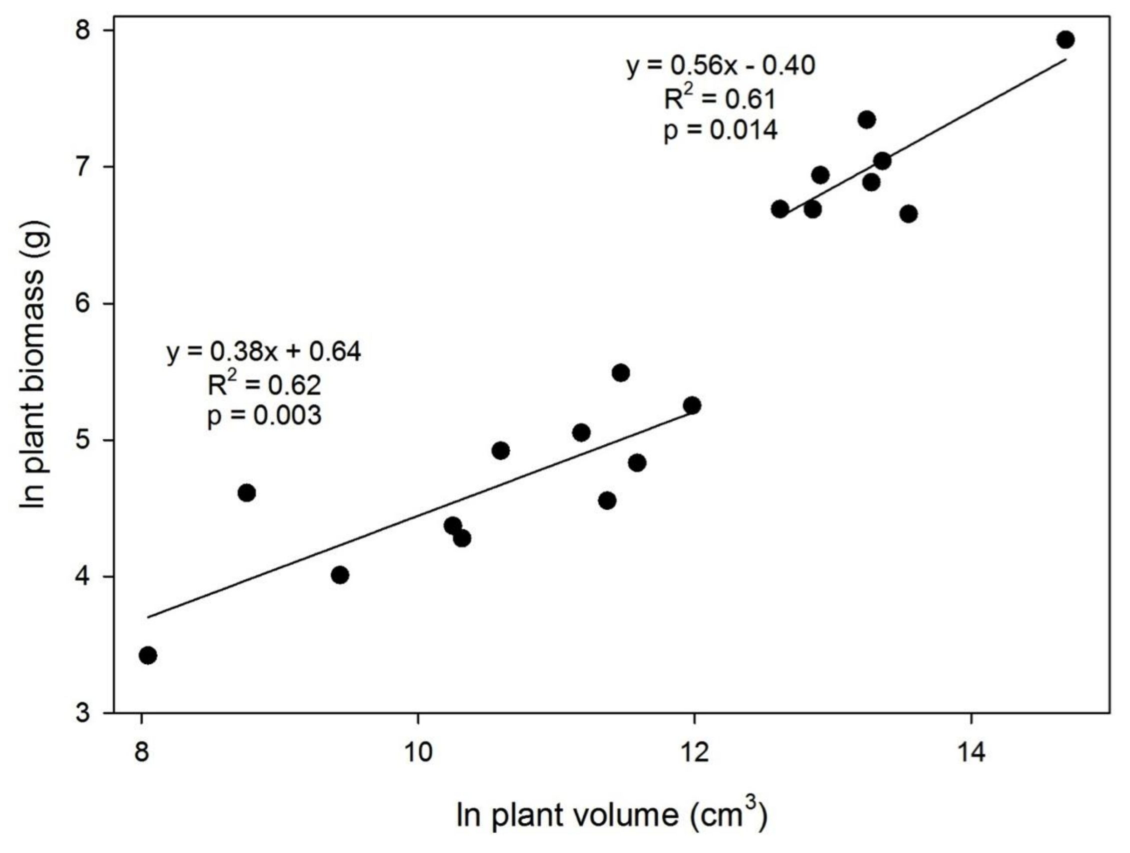
In order to calculate tree carbon concentrations, global default factors (based on tissue nutrient analysis) of 0.48 and 0.39 for above- and below-ground biomass, respectively, were used (Kauffman and Donato 2012). These values were subsequently multiplied by above and below-ground biomass to determine the total tree carbon. Values were expressed in units of MgC ha^{-1}.

4.1.2 Salt Marsh

In the laboratory, individual plants were separated into woody material and succulent tissue, and then weighed. A subsample of woody and succulent tissue from each plant was weighed, dried to a constant weight at 50°C, and weighed again to obtain a wet-to-dry mass conversion factor for converting the total wet weight of the entire plant to dry weight.

The relationship between dried biomass and plant volume (calculated by multiplying height by the two crown widths) was calculated using a simple linear regression with natural log-transformed data. Upon examination of the results, two different relationships became apparent depending on plant size (Figure 10). The regression equations were used to calculate biomass for all of the plants measured in each plot.

Tissue samples from a select number of plants were sent to the University of California, Davis Stable Isotope facility for determination of percent carbon and nitrogen. Carbon content of woody and succulent tissue averaged 40%; therefore, above-ground plant carbon content was determined by multiplying biomass by 40% and expressed in units of MgC ha^{-1}.



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 10

Relationship between *A. macrostachyum* volume and biomass based on plant size class.

4.2 Quantification of Subtidal Ecosystem Biomass

4.2.1 Seagrass

Living seagrass tissues (including both above- and below-ground components) were rinsed of the soil matrix, separated by species (and by component in the case of *H. uninervis* samples) and dried to a constant weight in a 50°C oven. Dry weight values were subsequently converted to carbon equivalents assuming a carbon content of the seagrass biomass of 35% of dry weight (Fourqurean *et al.* 2012). The area of the core tube was used to calculate living seagrass carbon per unit area, and values expressed as MgC ha^{-1}.

4.3 Soil Carbon Analysis

4.3.1 Seagrass, Mangrove, Salt Marsh, Algal Flat, and Coastal Sabkha

In the laboratory, soil samples were dried to a constant mass at 50°C and weighed to determine DBD (grams of soil per cubic cm). The dry samples were then homogenized by grinding them to a fine powder using a motorized mortar and pestle. Duplicate ca. 1g aliquots of each soil sample were transferred to pre-ashed and pre-weighed 20 cm^3 glass scintillation vials. The samples were then ashed in a furnace at 500°C for 6 hours until constant weight was reached. For each subsample, Loss on Ignition (LOI) was calculated as:

(*Equation 2*) **LOI = Initial dry weight – weight remaining after ashing initial dry weight x 100%**

Total Carbon (TC_{soil}) content of duplicate 30 mg aliquots of the dry soil subsamples was measured using an automated elemental analyzer (Fisons NA1500). In order to measure the Organic Carbon (C_{org}) content of the soil samples, the instrumental analyzer-furnace ashing procedures described by Fourqurean et al (2012) were used. The Inorganic Carbon content of the ash (IC_{ash}) remaining after the LOI measurements was determined using the elemental analyzer; this IC_{ash} value was scaled back to the original weight of the unashed sample using the LOI to calculate the Inorganic Content of the original soil (IC_{soil}). This was then calculated C_{org} (expressed in units of % of dry weight) as:

(*Equation 3*) $\boldsymbol{C_{org} = TC_{soil} - IC_{soil}}$

Carbon density (gC/cm^3) for each depth interval was calculated by multiplying the C_{org} value for each depth increment by the corresponding Dry Bulk Density (DBD). In order to calculate the carbon content of core segment ($CC_{segment}$), the following equation was used:

(*Equation 4*) $\boldsymbol{CC_{segment} = (z_{segment} \times \text{carbon density}_{segment})/100}$

where $z_{segment}$ is the length of the given depth interval. The product is divided by 100 to convert C_{org} units from % of dry weight to gC per g(dry weight). The total C_{org} was calculated by summing $CC_{segment}$ values from the length of each core.

4.3.2 Seagrass

Samples were dried at 50°C until constant weight was reached, and this dry weight was recorded. DBD was calculated as the dry weight of the soil subsamples divided by the volume of the subsample ($5cm^3$). The same methodology for measuring soil organic carbon in all other ecosystems was used for seagrass soil samples.

For calculations of areal carbon storage, estimates of C_{org} and DBD within a site were grouped into 10cm depths increments, starting with the surface 10cm (i.e., all soil in the top 10cm of the core), followed by 10-20cm, then 30-40cm, and so forth until the deepest part of the core was reached. The carbon content (CC) of each 10cm depth increment of each core was calculated from the measured C_{org} and DBD from all subsections within a depth range:

(*Equation 5*) $CC_{slice} = z_{slice} \times Mean(DBD_{slice}) \times Mean(Corg_{slice}) / 100$

where z_{slice} is the thickness of the slice, $Mean(DBD_{slice})$ was the average of all DBD values from the stated depth increment from all cores taken at a site, and $Mean(Corg_{slice})$ was the average of all C_{org} values from the stated depth range at a site, divided by 100 to convert C_{org} units from % of dry weight to gC per g(dry weight).

An estimate of the precision of our estimate of the CC per slice was obtained using the standard estimate for propagation of errors in the product of two numbers:

(*Equation 6*)

where σ_{CC} is the standard deviation of the *CC* per slice, *DBD* is the Mean DBD per slice, C_{org} is the Mean C_{org} per slice, σ_{DBD} is the standard deviation of the DBD values and σ_{Corg} is the standard deviation of the C_{org} values in each slice. Total organic carbon of a soil core was calculated as the sum of the CC_{slice} vales for all of the slices in the core:

(*Equation 7*) ***Total Soil Organic Carbon = i = 1nCCi***

Where *i* represents each core slice and n represents the total number of 10 cm slices from each site. Total organic carbon was converted to units of $MgC\ ha^{-1}$. Estimates of the standard deviation of the total organic carbon ($\sigma_{organic\ carbon}$) for each site were calculated using the standard method for propagation of errors in a summation:

where σ_{0-10} is the σ_{CC} for the 0-10 cm slice, et cetera.

4.4 In Situ Data Processing and Analysis

4.4.1 Elevation and Tidal Analysis

To process the static elevation data to yield a survey-grade control point, a technique known as Precise Point Positioning (PPP) was utilized. PPP is a method that performs precise position determination using a single GPS receiver. Since there is not a network of permanent GPS base station throughout the UAE, PPP was the chosen technology to process the data. Post processing outside of UAE consisted of downloading precise satellites orbits and clock data from the International GNSS Service (IGS). Using orbit data from the IGS enabled the computation of positions within the International Terrestrial Reference Frame (ITRF) and vertical data relative to the World Geodetic Survey Ellipsoid of 1984 (WGS 84). Once each base station point was processed, both the base station point data and associated rover transect data were imported into *Leica Geo-Office* processing software. During data collection, all of the rover position and elevations are related to the position and elevation of the base station. Since the base station was not fixed during rover data collection, the rover points have to be adjusted in position and elevation based on the processed position and elevation of the base station. *Leica Geo Office* enables the adjustment of all points based on the PPP processing.

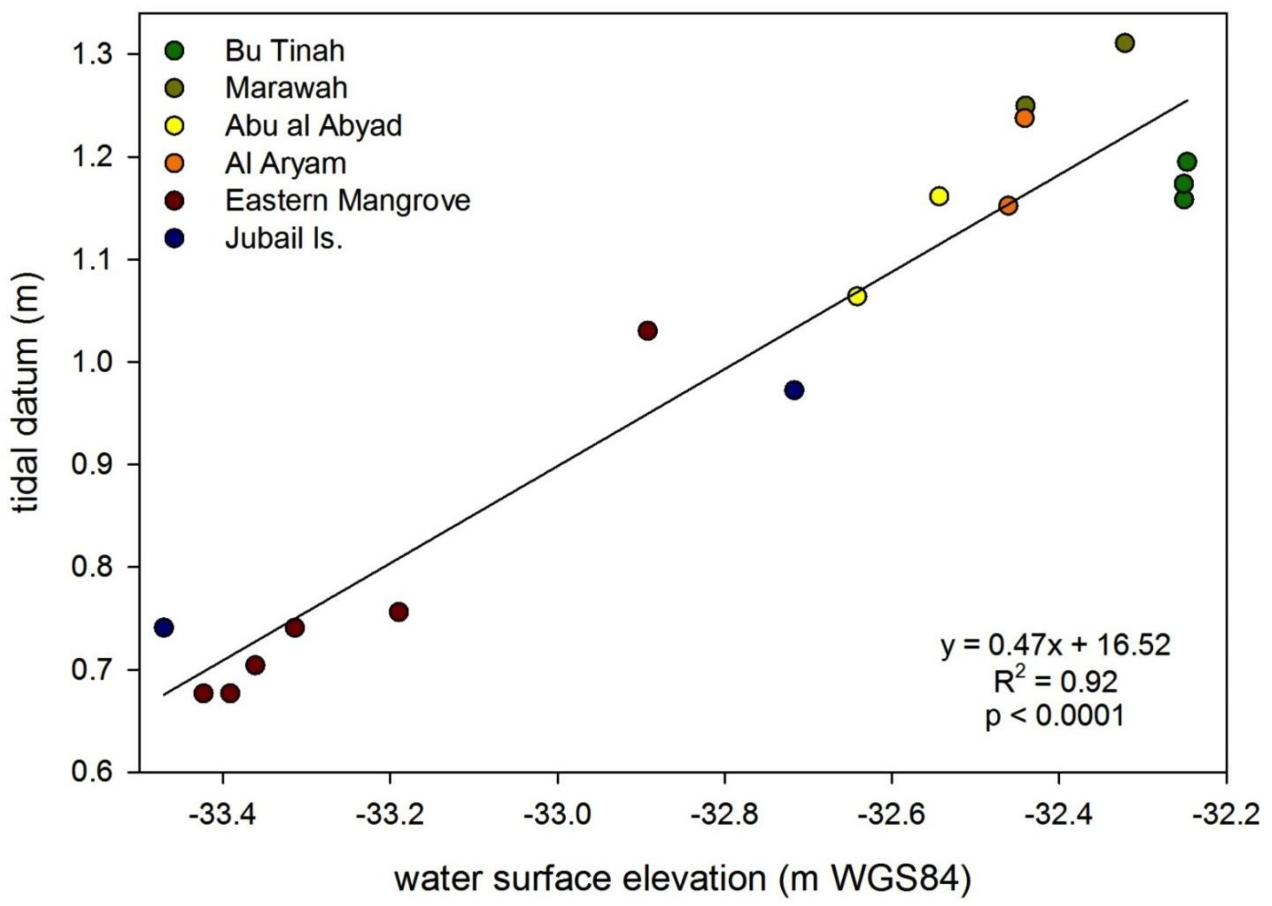
To relate survey elevations to tidal elevations, five years of predicted tidal data from five locations across the Emirate (Abu Al Abyad, Ras Zubayyah, Khwar Ghanadah, Umm An Nar, and Fasht Al Bazam) were obtained using tide software (Nobeltec Tides and Currents software). Data were logged in 15 minute intervals and in presented in the United Kingdom Hydrographic Office (UKHO) datum. All high and low tides were identified using a script in the R statistical program and yearly calculations of mean high water (MHW), mean low water (MLW), and mean tide level (MTL) were computed (Table 6). Additionally, tidal elevations that corresponded to surveyed water level elevations were identified and a relationship between the values was determined using a simple linear regression (Figure 11). Using the regression equation, all surveyed elevations were transformed into the UKHO datum.

Table 6 Seagrass cover class using the Braun-Blanquet scale

Score	Interpretation
0	Species absent from quadrat
0.1	Species represented by a solitary short shoot, < 5% cover
0.5	Species represented by a few (< 5) short shoots, < 5% cover
1	Species represented by many (> 5) short shoots, < 5% cover
2	Species represented by many (> 5) short shoots, 5-25% cover
3	Species represented by many (> 5) short shoots, 25-50% cover
4	Species represented by many (> 5) short shoots, 50-75% cover
5	Species represented by many (> 5) short shoots, 75-100% cover

In order to transform surveyed elevation relative to the tidal datum (i.e., MHW and MTL), the following equation was used:

This transformation enables elevation comparisons across the Emirate to occur despite the differences in tidal patterns from East to West and from the Arabian Gulf inland.



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 11

Relationship between field-surveyed water surface elevations and concurrent tide heights.

4.4.2 Pore-water chemistry

To determine pore-water sulphate and chloride content, samples were diluted by 400 (except for a 1600 dilution for Thumayriyah samples) and concentrations in mg/L were measured using a Dionex ICS-2000 ion chromatography system. Pore-water methane concentrations were measured using a Varian 450-GC gas chromatograph and converted to parts per million (ppm) using a standard curve.

4.5 Statistical Analysis

To examine differences in total soil depth and soil carbon stock at different depths (10cm, 30cm, 50cm, 100cm, and total depth) across ecosystems, two analysis of variance (ANOVA) tests were run. The data met the assumptions of normality and homogeneity of variance so no transformation was needed. The least square means were used to assess differences across ecosystems, if any, and the standard significance value of 5% was chosen.

5 Results

The results are described by carbon stock to provide inter-ecosystem comparison.

5.1 Soil Carbon Stocks

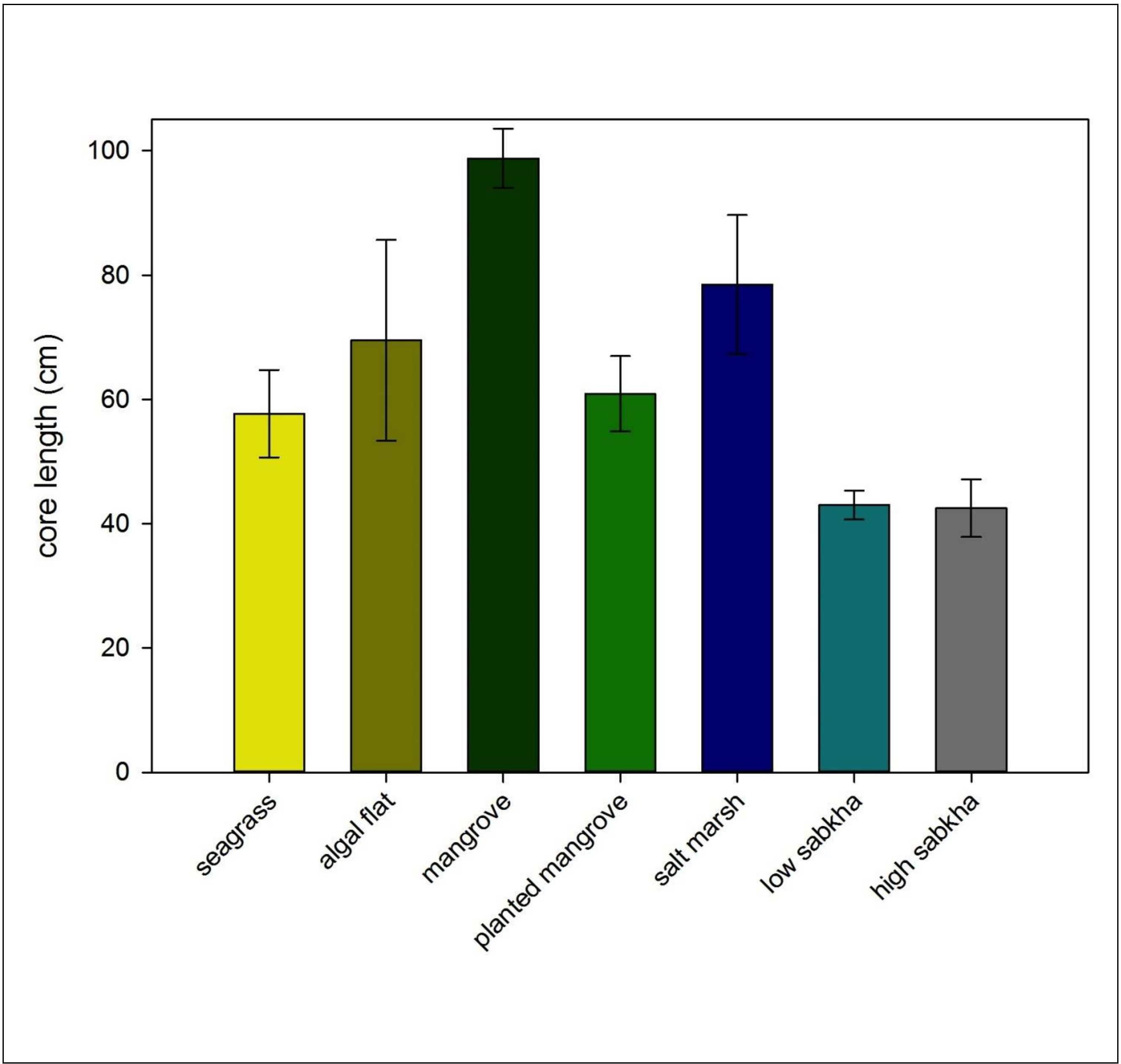
The average soil depth did not vary significantly across all ecosystems ($F_{5,40}$ = 1.05, p = 0.40; Figure 12). Soil depths ranged between 8.5 and 100cm for seagrasses, 13 and 200cm for algal flats, 8 and 300cm for mangroves, 12 and 100cm for planted mangroves, 10 and 200cm for salt marshes, and 27 and 65 cm for coastal sabkha. We did not include the soil data from the 15 year-old planted mangrove at Abu Al Abyad in subsequent analyses because the values were deemed abnormally high for this type of sediment, with many DBD values above 1.9 g cm^{-3}.

Average dry bulk density (DBD), which is the mass of dried sediment per cubic cm, was the lowest in the mangrove and algal flat ecosystems and highest in the seagrass ecosystems; DBD did not vary greatly otherwise (Figure 13a). The DBD ranged from 0.137 – 1.562 g cm^{-3} for mangroves, 0.505 – 1.712 g cm^{-3} for salt marshes, 0.77 – 1.84 g cm^{-3} for planted mangroves, 0.632 – 1.726 g cm^{-3} for coastal sabkha, and 0.566 – 1.699 g cm^{-3} for algal flats. DBD was the lowest overall within the top 15cm of soil at the mature mangrove sites (Figure 13b), averaging 0.72 g cm^{-3}. DBD in seagrass soils increased in the top 15cm of soil and consistently was higher at lower depths compared to other ecosystems. In general, however, no clear patterns were detectible across the other ecosystems (Figure 13b). The soils underlying the seagrass beds were mainly silty sands with DBD that ranged from 0.49 to 1.82 g cm^{-3} (Figure 14a), with a mean of 1.37 ± 0.04 g cm^{-3} (±1 SE; n = 471 samples). Compared to values from global seagrass beds (Fourqurean *et al.* 2012), DBD values in these samples was relatively high (Figure 14b). Organic content (C_{org}) of the soil samples ranged from below detection (less than 0.05%) to a maximum of 2.44%, averaging 0.64 ± 0.39 % (n = 469; Figure 15a).

The relationship between DBD and the proportion of soil organic carbon followed a curve that has been reported by many in other wetland ecosystems (Figure 16). There is an inverse relationship between DBD and soil organic carbon. DBD was the greatest when soil organic carbon is lowest and dropped off exponentially as the proportion of organic carbon increased (Figure 16). Mature mangroves were the only sites with soil organic carbon values greater than 10% (Figure 16) and this agrees with field observations of peat layers in mature mangrove sites (Figure 17a).

Soil carbon density varied widely across ecosystems, soil depths, and sites (Figures 18 and 19). In algal flat and mature mangrove ecosystems (Figures 18abf), carbon density tended to be the highest (meaning more carbon per unit volume) in the top 15cm of soil and decreased with depth. Algal flats had the highest carbon density of all the ecosystems at the soil surface (Figure 18f), followed by mature mangroves (Figure 18ab). No strong pattern was detectible in salt marsh or coastal sabkha ecosystems (Figure 18cg); however, buried algal layers were observed in some cores. What appeared to be a buried mangrove paleosol was also found at the Al Aryam salt marsh (Figures 17b and 18c) and buried algal mats at Algal Moon (Figure 18f) and Sabkha Moon (Figures 17c and 18g). In planted mangroves, there was no clear pattern of carbon density with depth, and values tended to be very low (Figure 18de); however, cores from the 10 year-old site at Jubail Island showed a consistent trend of carbon accumulation at the soil surface (Figure 18d). The majority of seagrass beds had low carbon density values, less than 0.015 g cm^{-3}, although Umm Al Hatam, Marawah, Fasht al Bazam, and Jazirat had value up to 2 g cm^{-3}. Carbon density tended to decrease with depth, but there was no consistent pattern and wide variation within and across sites.

No consistent patterns in soil carbon pools with soil depth were detected, as there was high variability both within and across ecosystems (Figure 20), and with sample size (Table 1). In the top 10 cm, mature mangroves had significantly greater carbon stocks than seagrass ecosystems (model: $F_{5,40}$ = 4.10, p = 0.012; least squares means difference, p = 0.0036; Figure 20) but none of the other ecosystems varied significantly (least squares means, $p > 0.08$). With the exception of seagrasses, which had the lowest overall soil carbon stocks on a per area basis, no statistically significant differences across ecosystems were detected as deeper soils were incorporated (Figure 20). Seagrass carbon pools were significantly less than mangroves, algal flats and coastal sabkha at 30cm depth (model: $F_{5,40}$ = 4.84, p = 0.0042, least squares means difference, $p < 0.02$), algal flats and coastal sabkha at 50cm depth (model: $F_{5,40}$ = 5.02, p = 0.0012, least squares means difference, $p < 0.02$), planted mangroves at 100cm depth (model: $F_{5,40}$ = 3.53, p = 0.0097, least squares means difference, p = 0.018), and mature mangroves at the total depth (model: $F_{5,40}$ = 3.5, p = 0.01, least squares means difference, p = 0.016). Total carbon stored in the soils of Abu Dhabi seagrasses ranged from a minimum of 1.9 MgC ha^{-1} at Al Dabiya 1 to a maximum of 109.0 MgC ha^{-1} at Umm al Hatam (Table 10, Figure 21a). The very low C stocks of some sites were attributable to the shallow soils at those sites. The mean C stores of the 18 sites sampled was 49.1 +/- 7.0 MgC ha^{-1}.

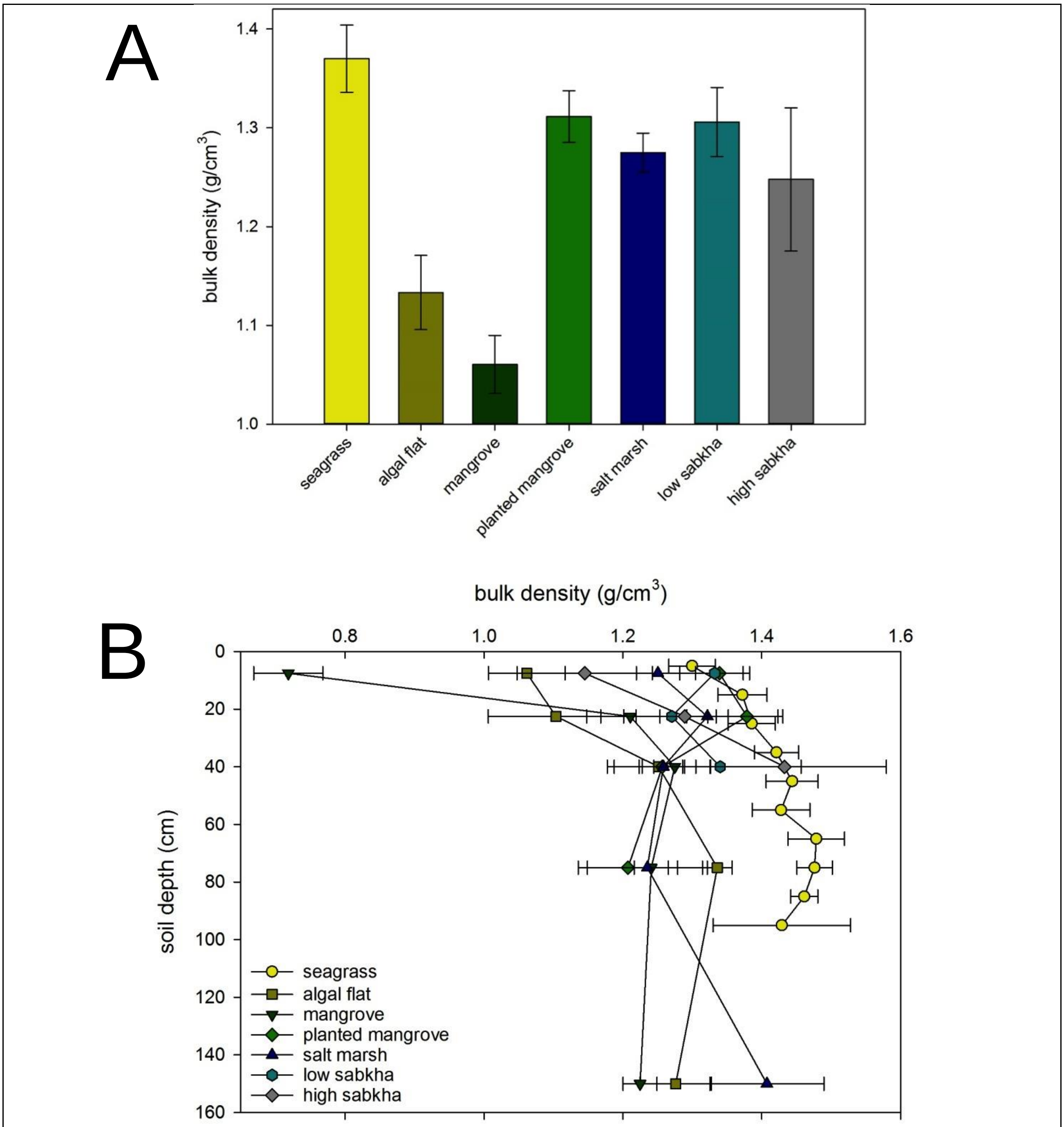


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 12

Average length of soil cores collected in each ecosystem (error bars = ±1 SE).

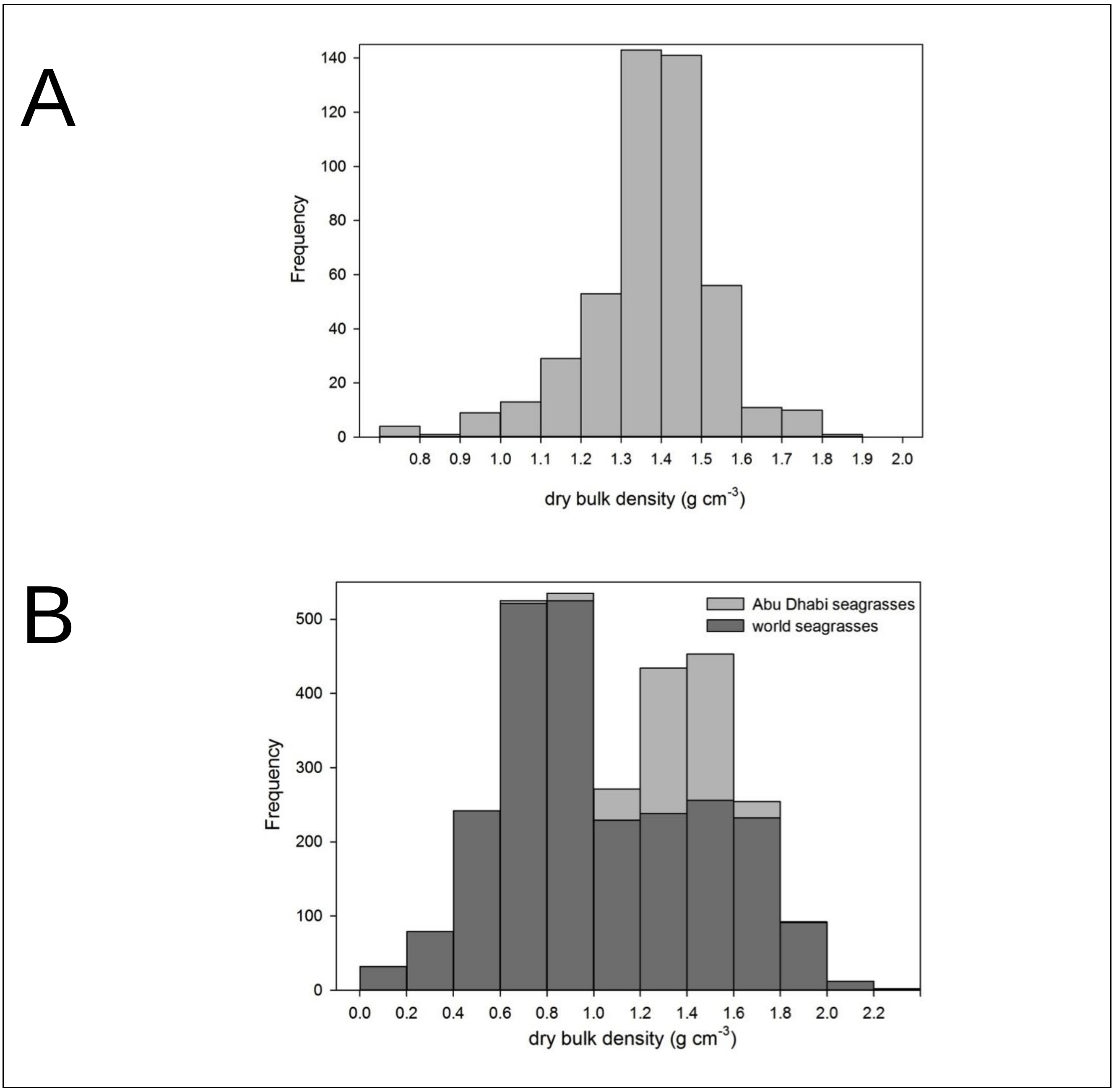


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 13

Average dry bulk density averaged within soil increments by a) ecosystem and b) ecosystem and within soil depth increments (error bars = ±1 SE).

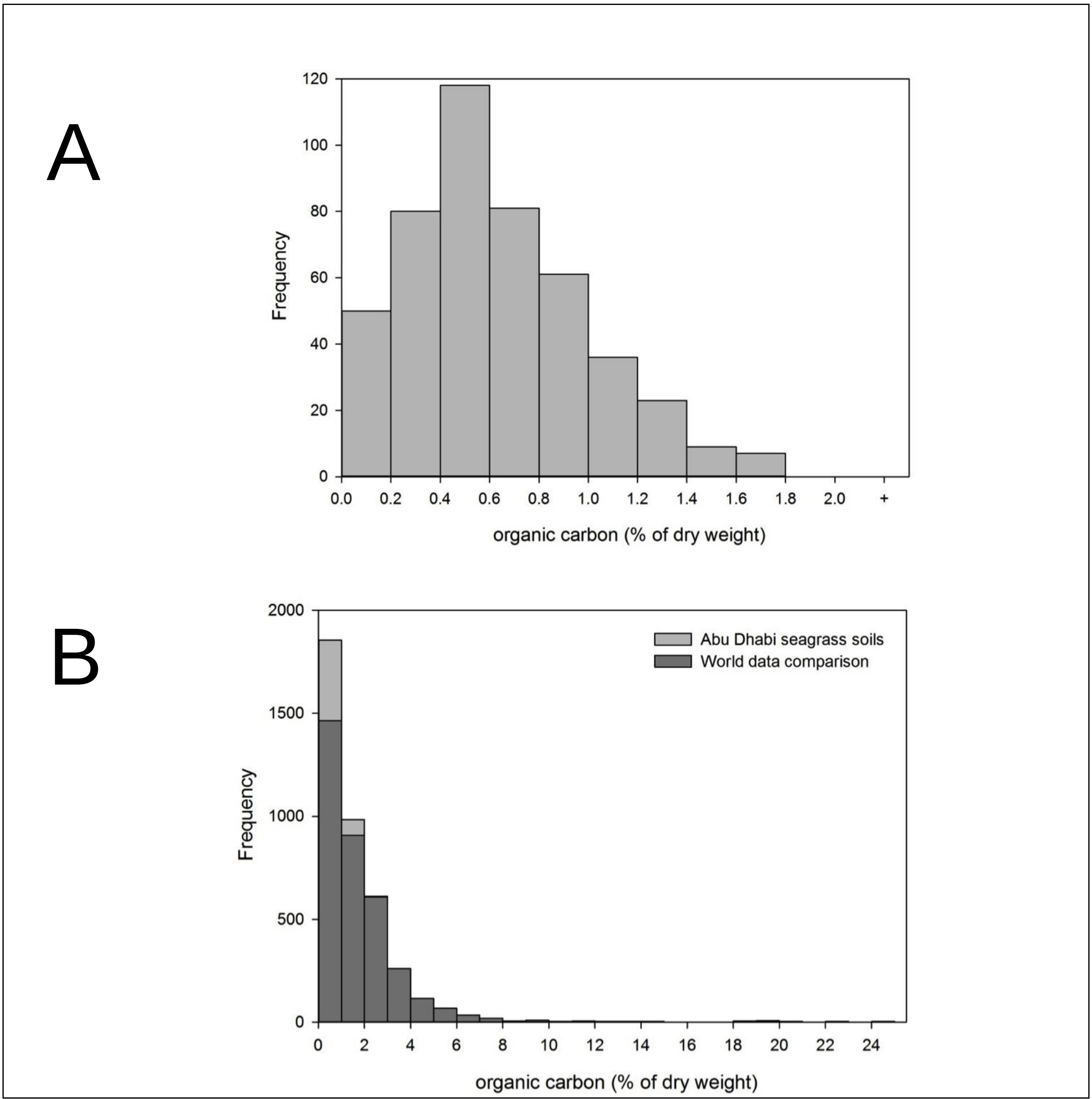


SOURCE: Abu Dhabi Blue Carbon Project; Fourqurean et al. 2012

Abu Dhabi Blue Carbon Project

Figure 14

Dry bulk density histograms for a) Abu Dhabi soils and b) world and Abu Dhabi soils.

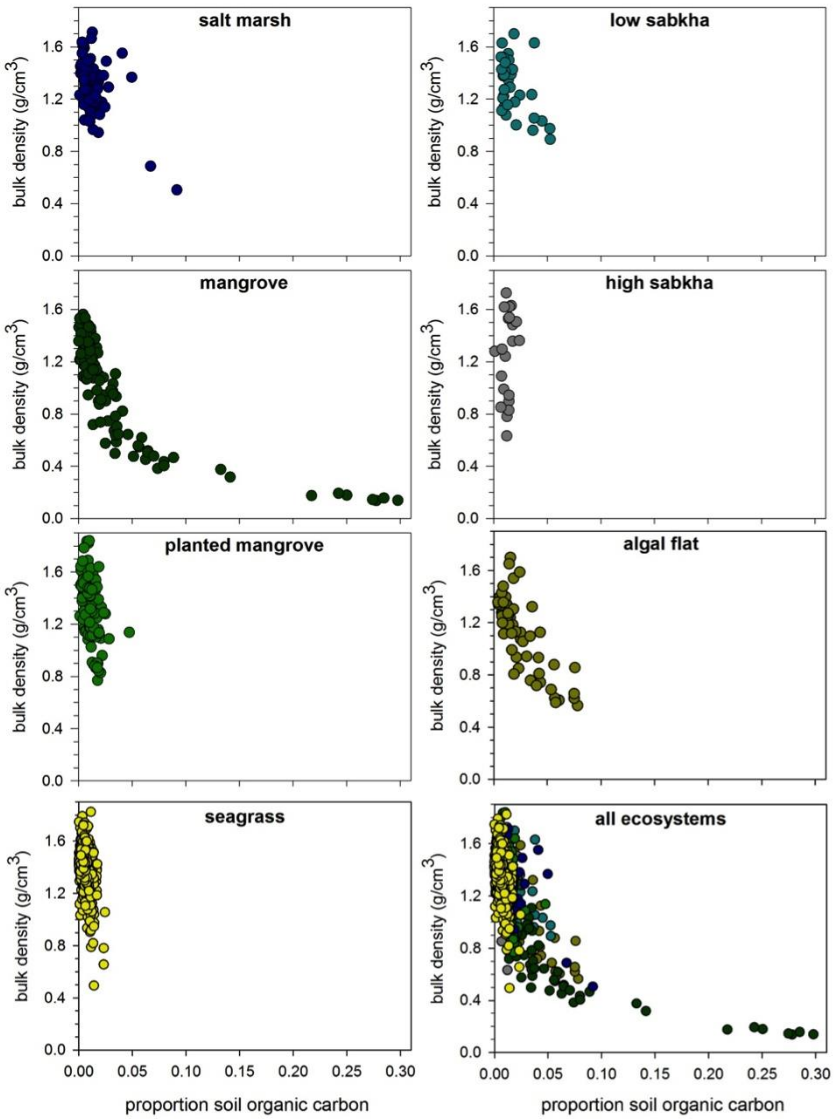


SOURCE: Abu Dhabi Blue Carbon Project; Fourqurean et al. 2012

Abu Dhabi Blue Carbon Project

Figure 15

Percent organ carbon in a) Abu Dhabi soils and b) world and Abu Dhabi soils.

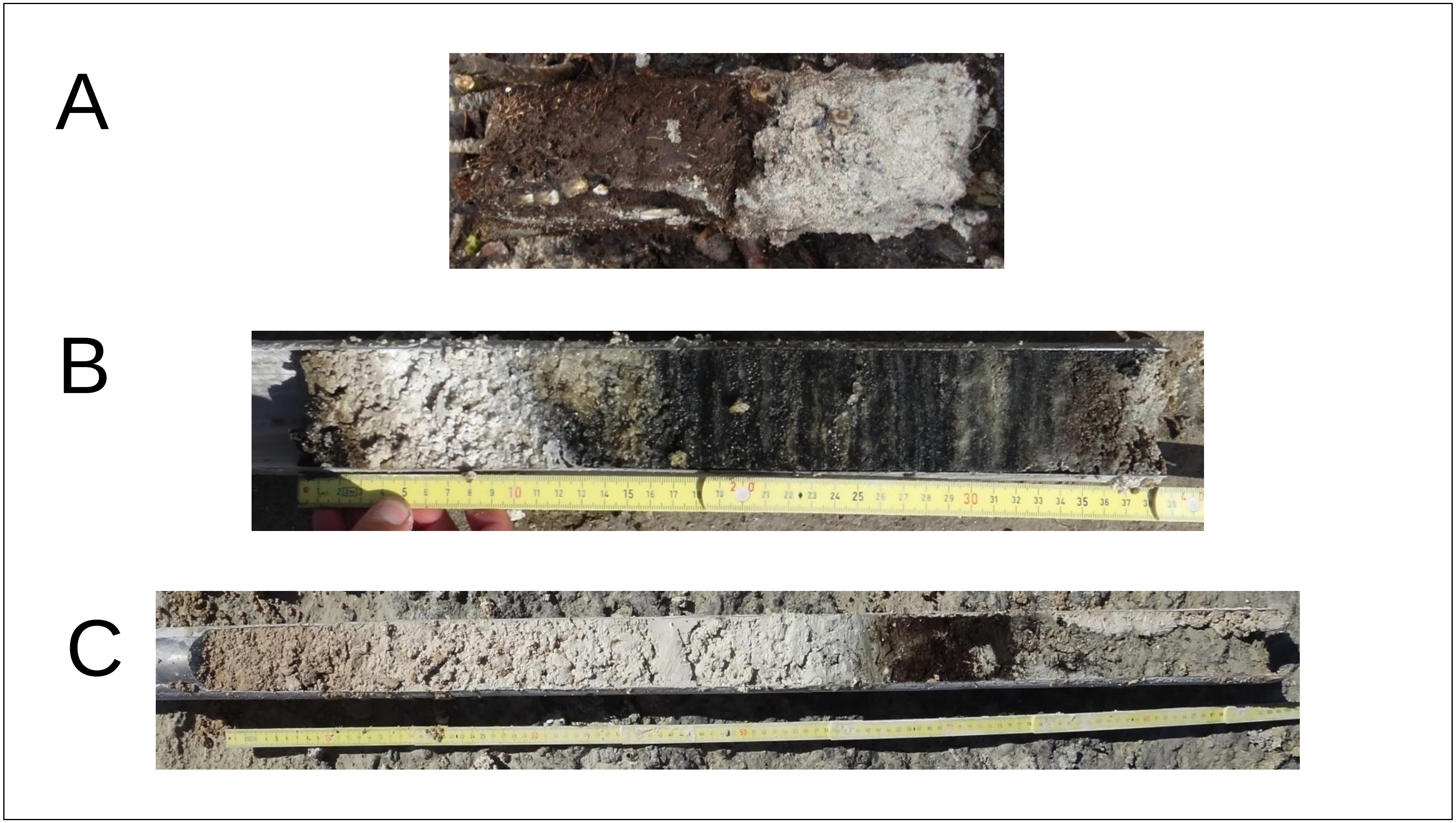


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 16

Relationship between the proportion of soil organic carbon and bulk density in all ecosystems.

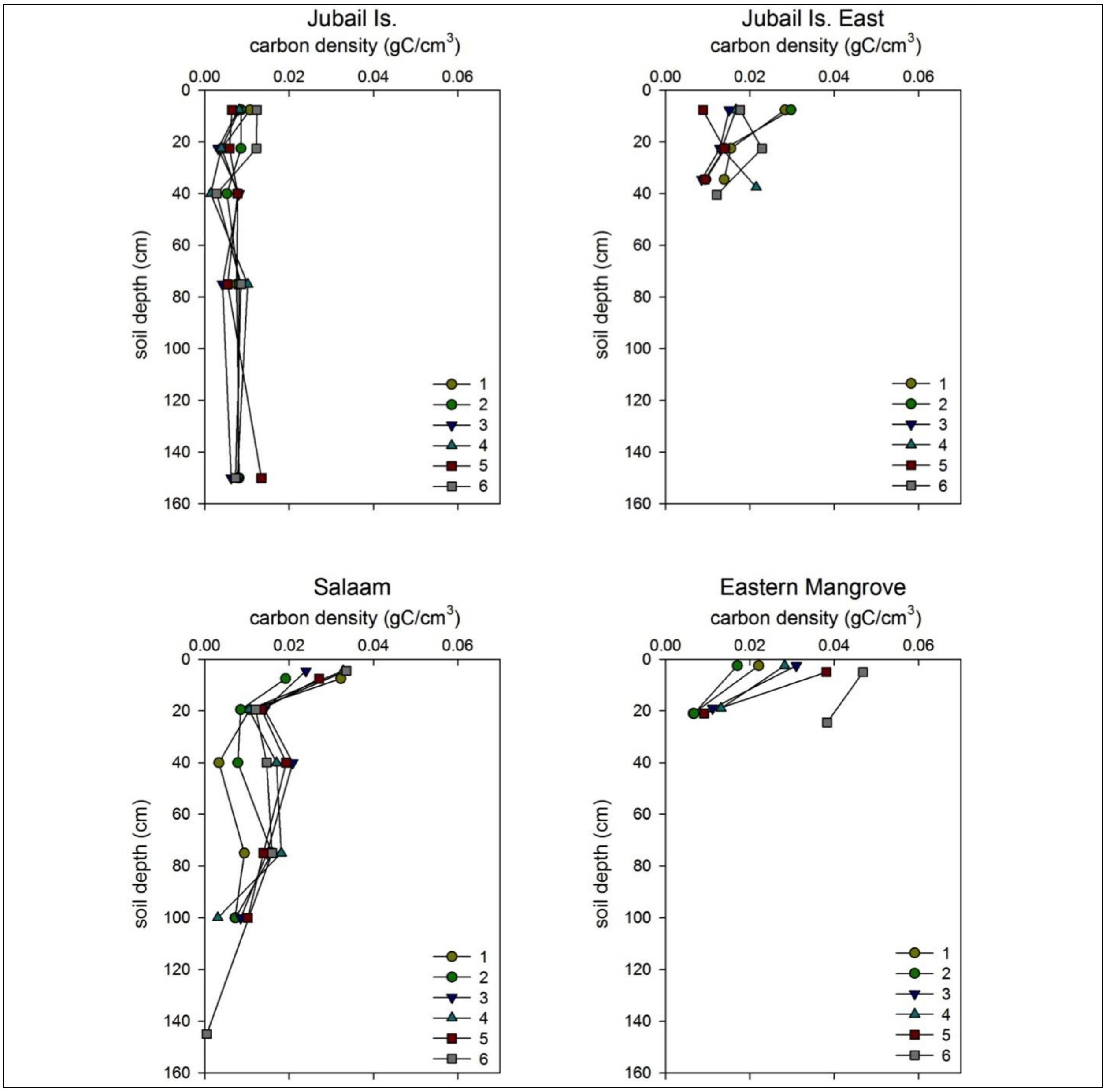


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 17

Soil cores with a) mangrove peat (Bu Tinah) b) buried algal mats (Sabkha Moon low sabkha) and c) buried mangrove paleosols (Al Aryam salt marsh). The top of the core is on the left.

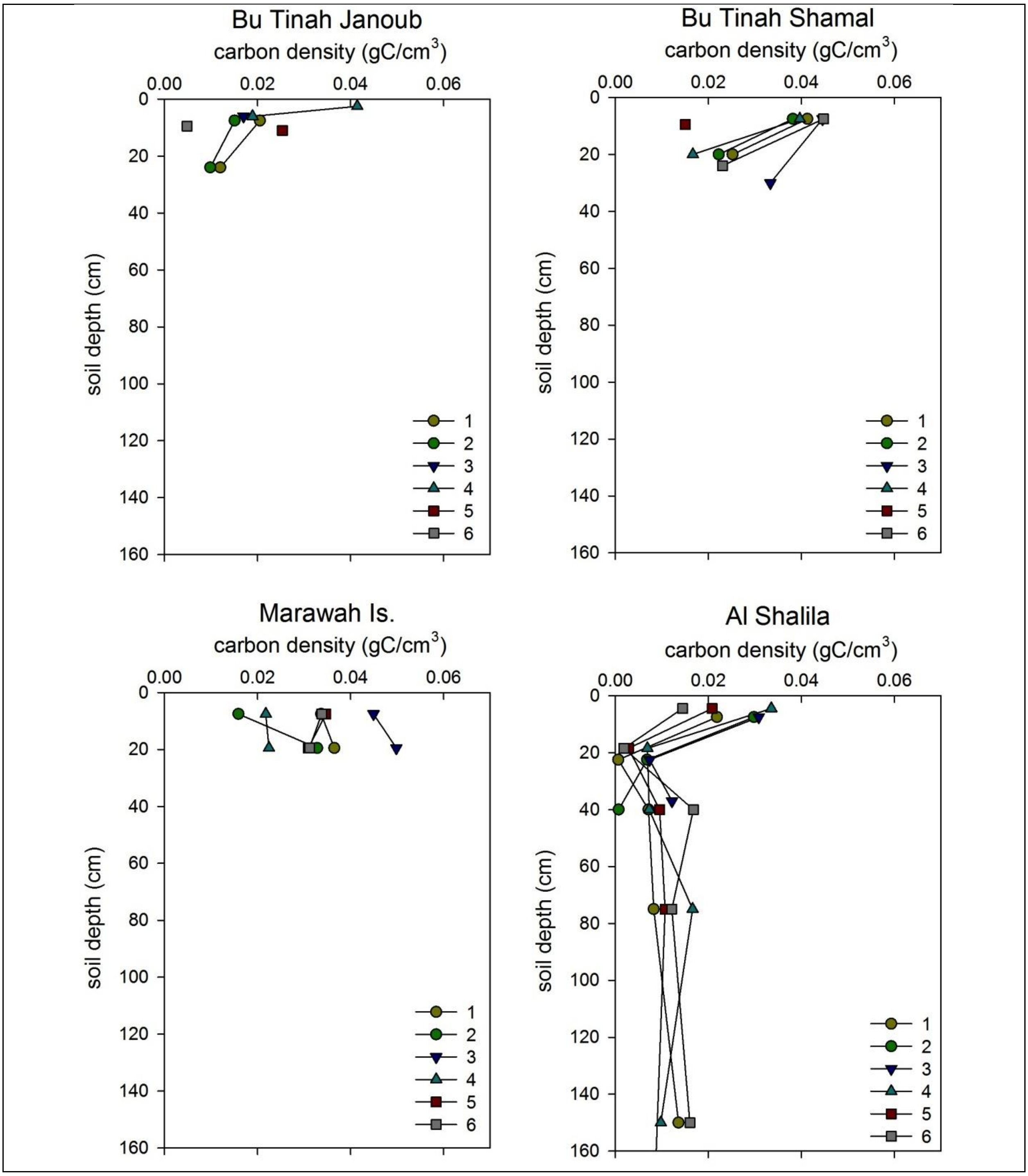


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18A

Carbon density with depth for soil cores collected at Eastern Mangrove & Jubail Is. mangroves.

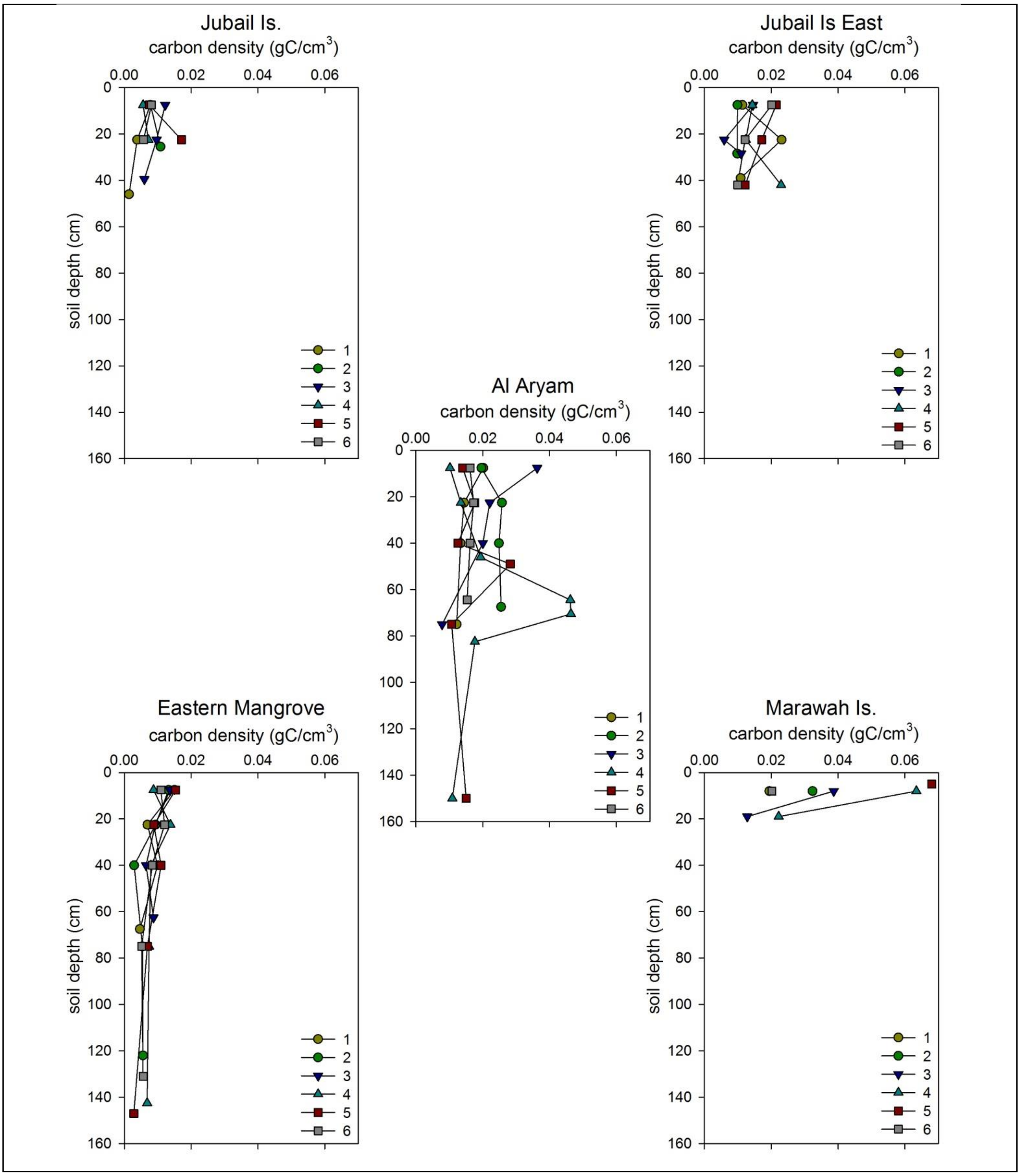


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18B

Carbon density with depth for soil cores collected at Bu Tinah, Marawah, & Al Shalila mangroves.

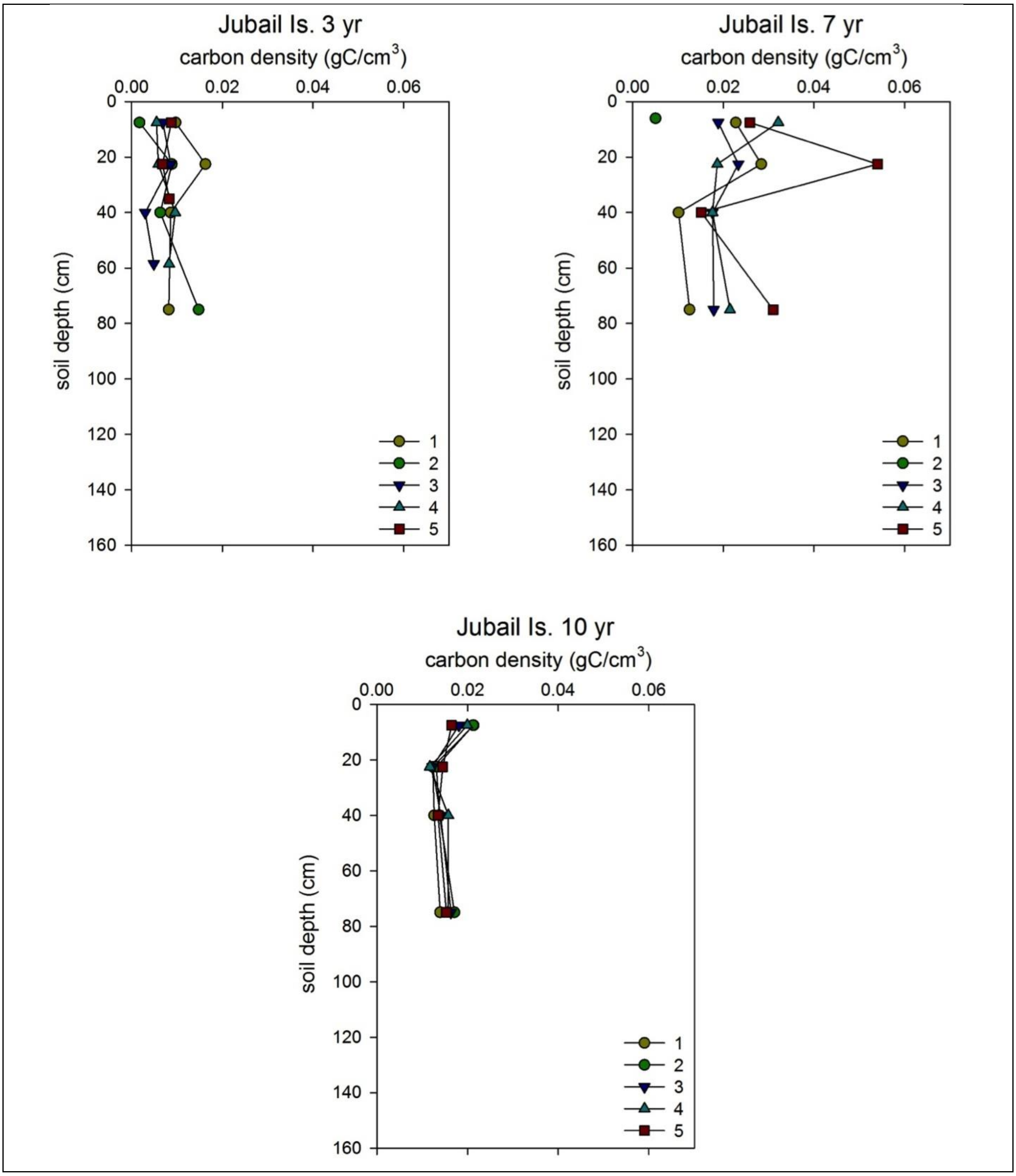


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18C

Carbon density with depth for all soil cores collected at each salt marsh.

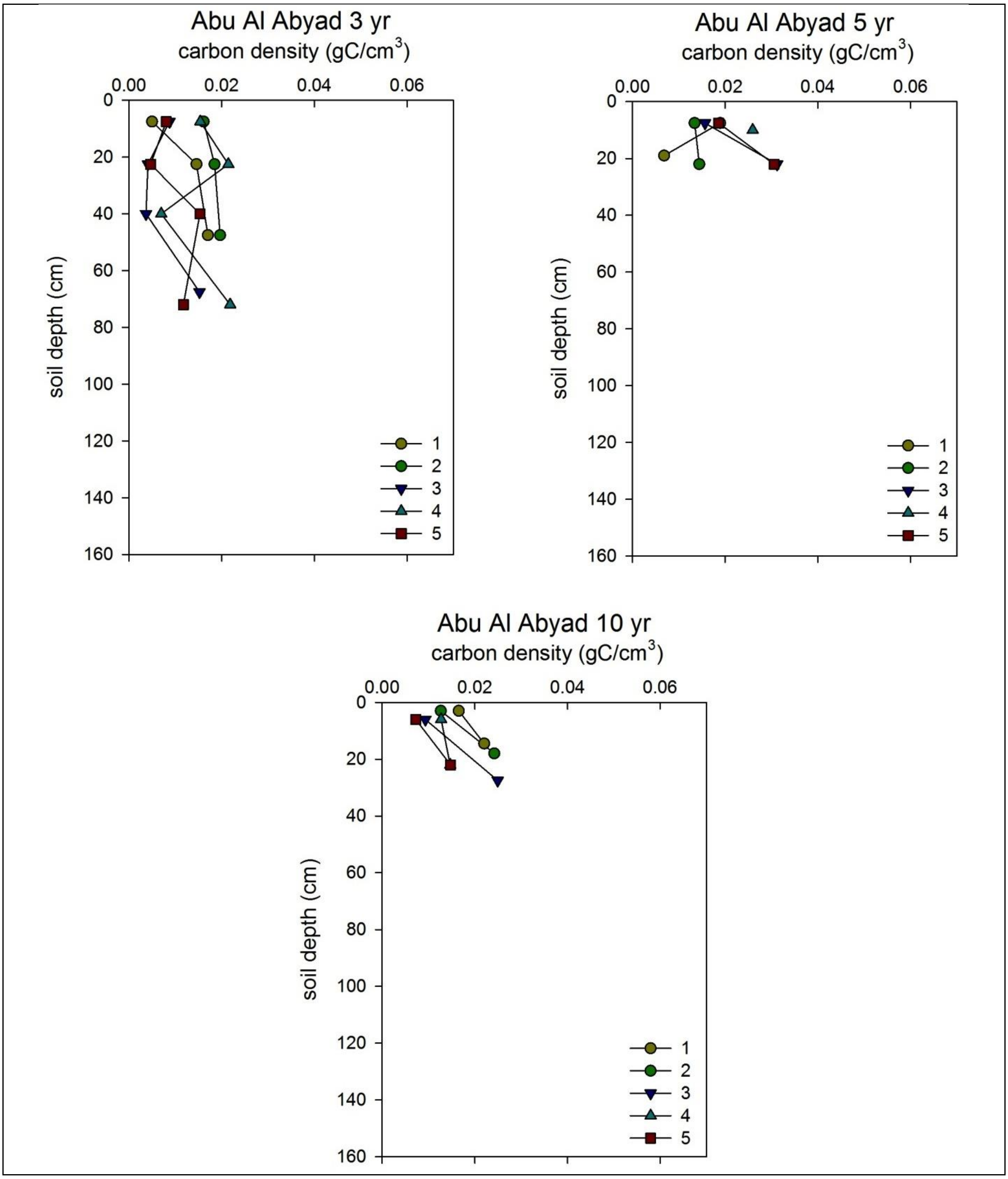


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18D

Carbon density with depth for all soil cores collected at Jubail Island planted mangroves.

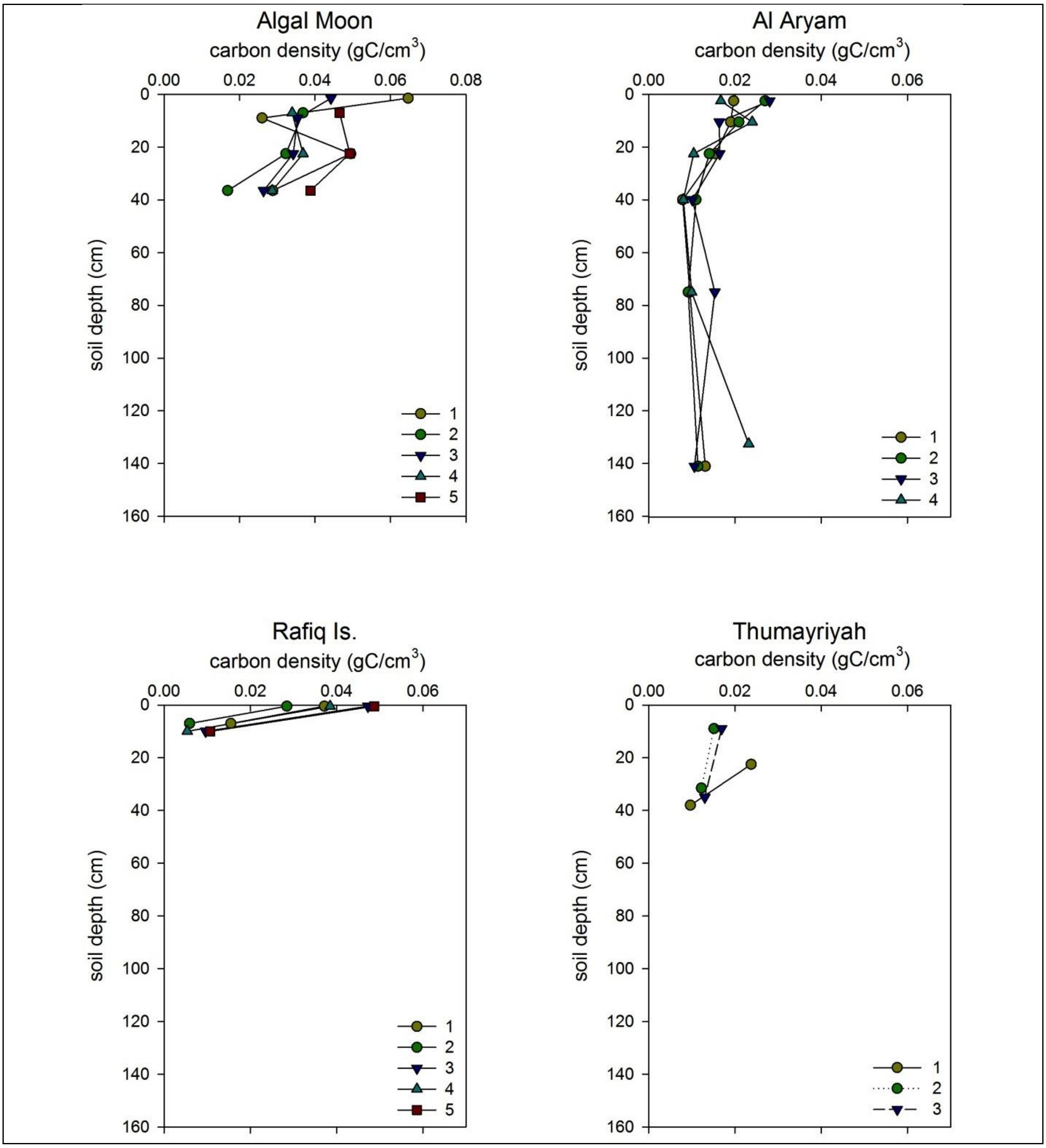


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18E

Carbon density with depth for all soil cores collected at Abu Al Aryam planted mangroves.

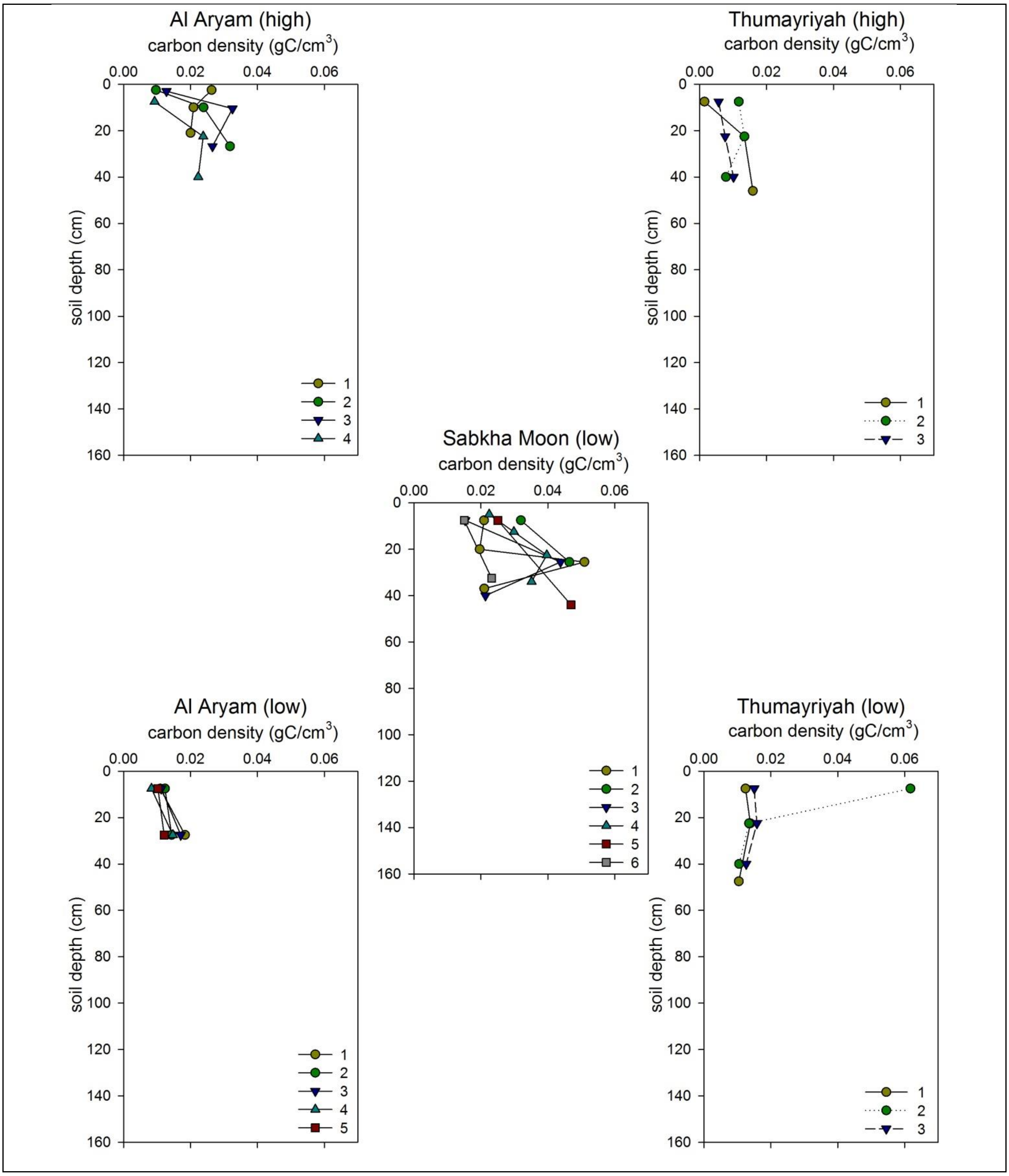


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 18F

Carbon density with depth for all soil cores collected at each algal flat.

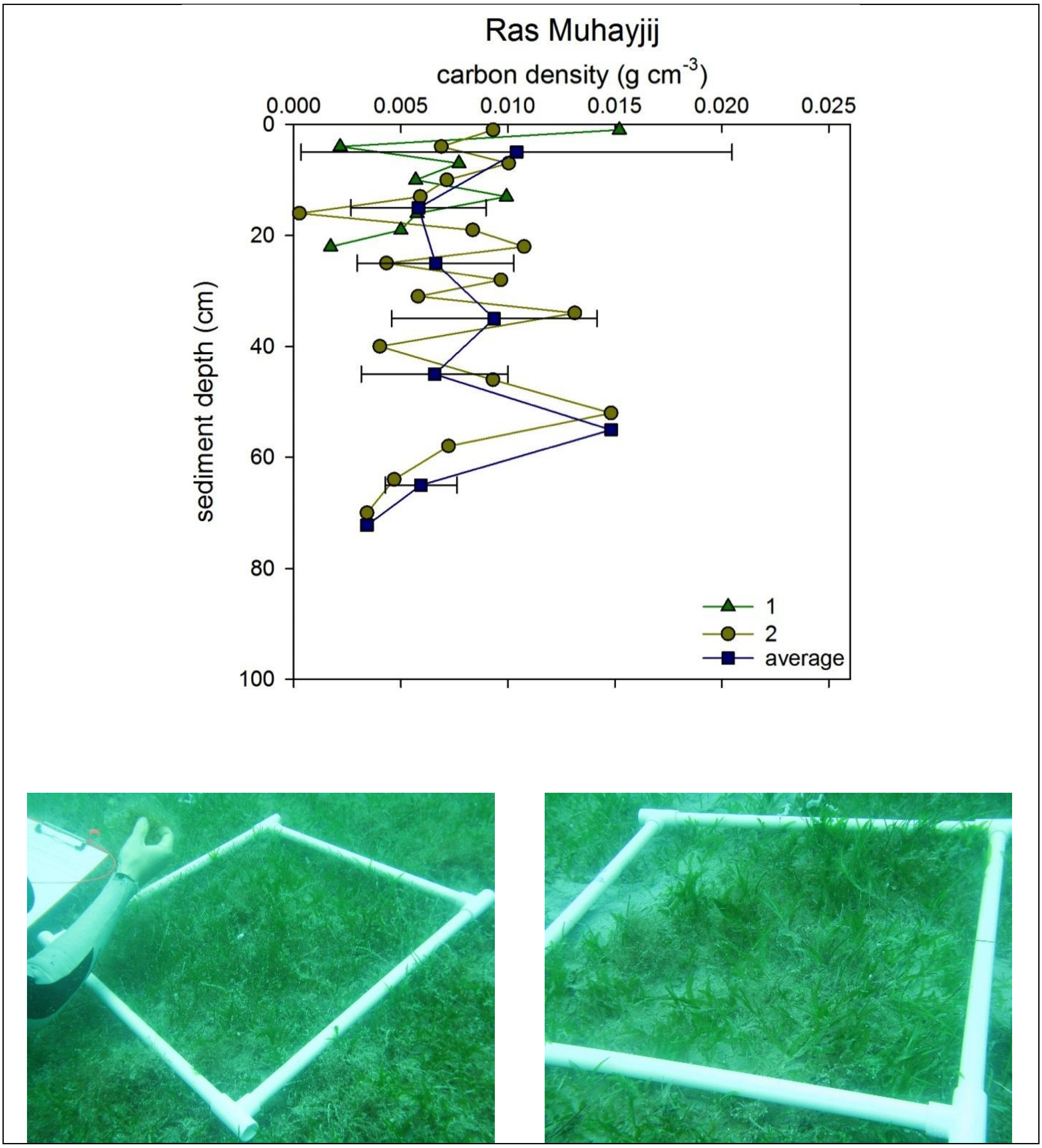


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

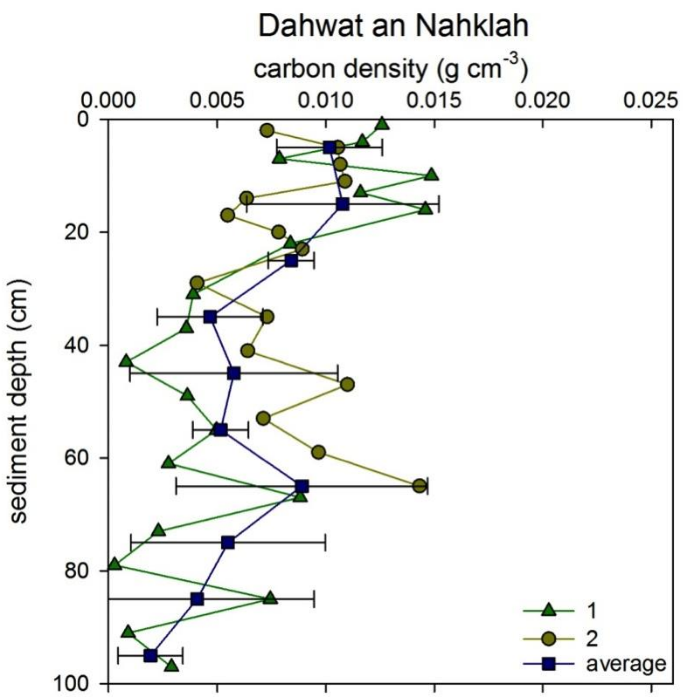
Figure 18G

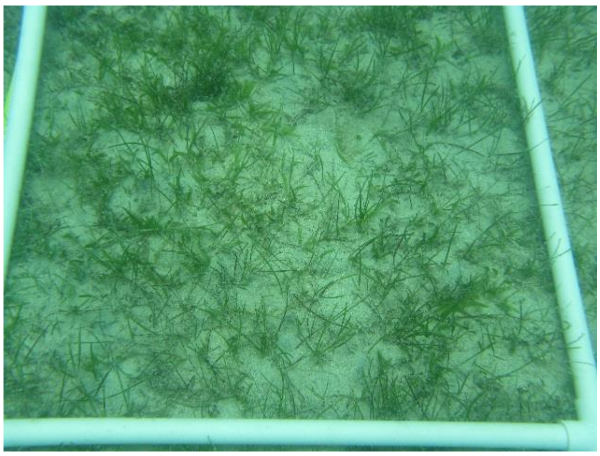
Carbon density with depth for all soil cores collected at each sabkha.



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project
Figure 19A
Carbon density profile of seagrass soil at Ras Muhayjij (error bars = ±1 Std).



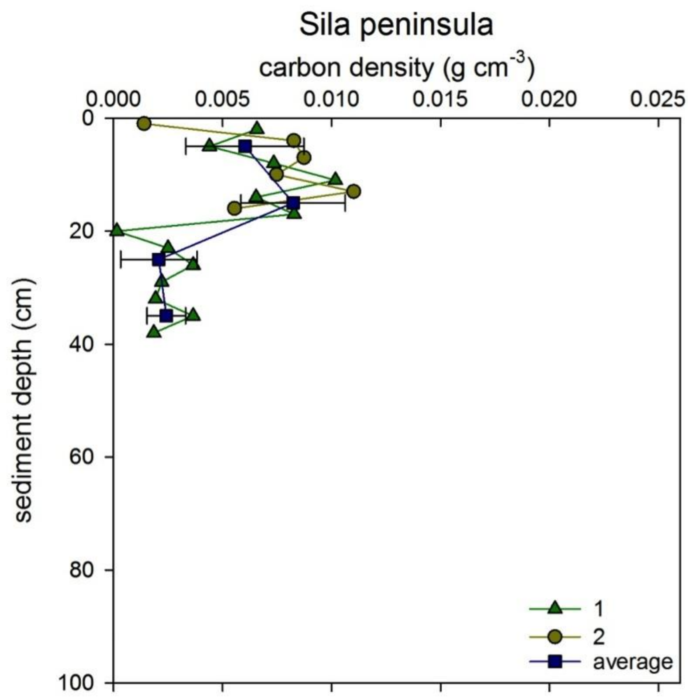


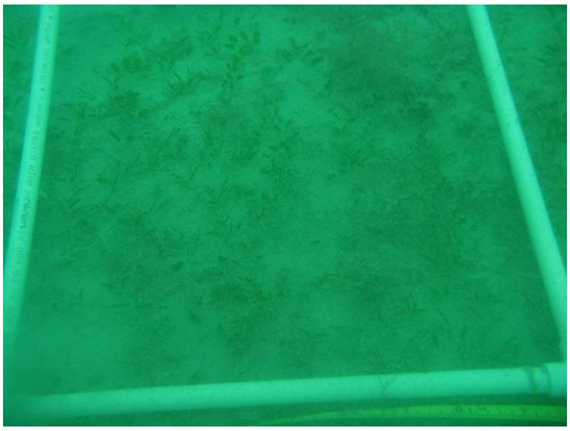
SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19B

Carbon density profile of seagrass soil at Dahwat an Nahklah (error bars = ±1 Std).



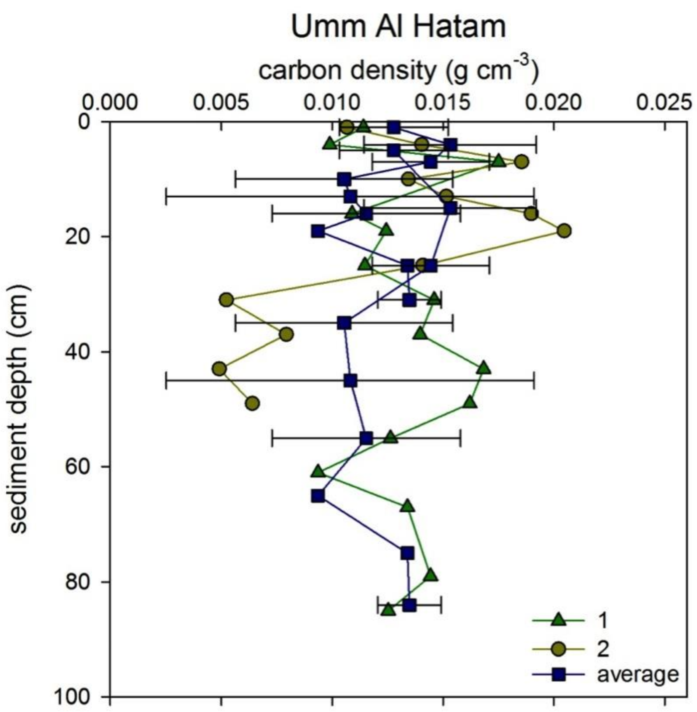


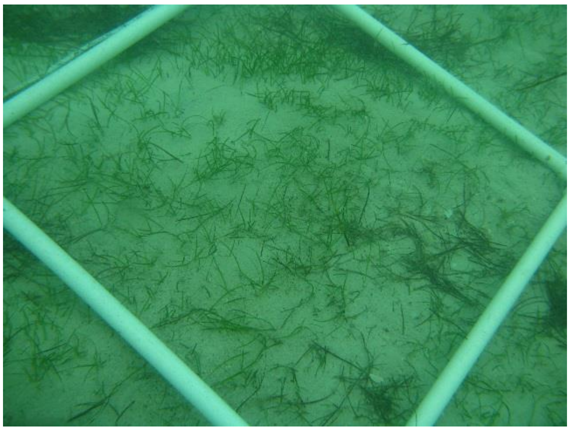
SOURCE: Abu Dhabi Blue Carbon Project

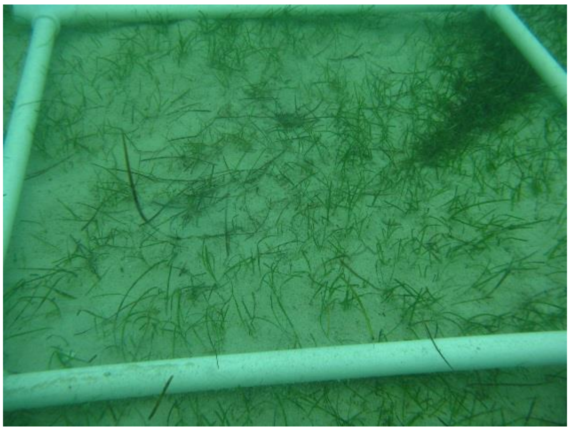
Abu Dhabi Blue Carbon Project

Figure 19C

Carbon density profile of seagrass soil at Sila peninsula (error bars = ±1 Std).





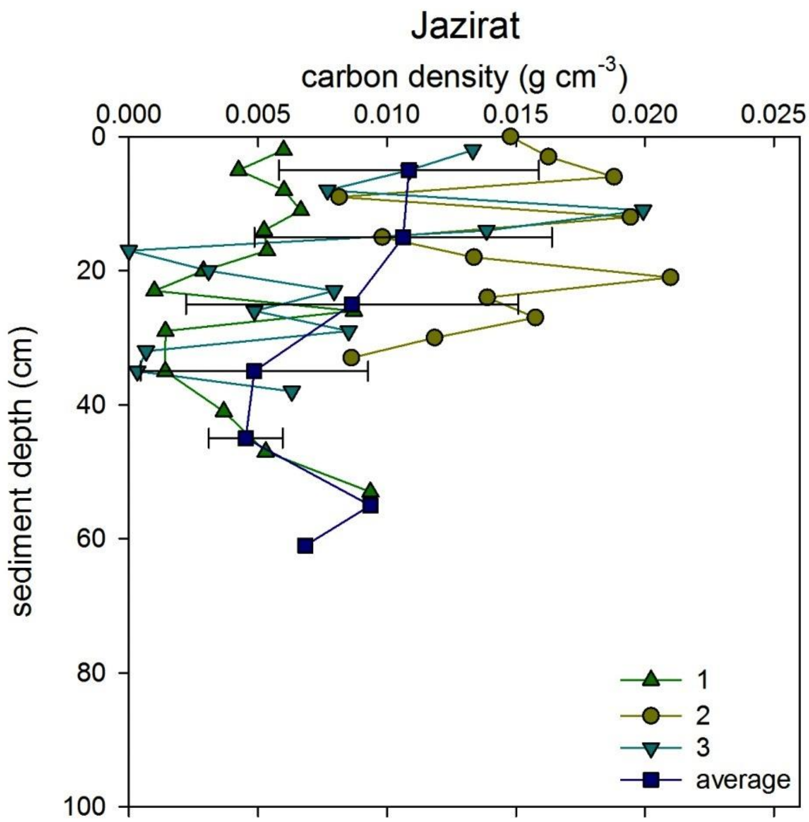


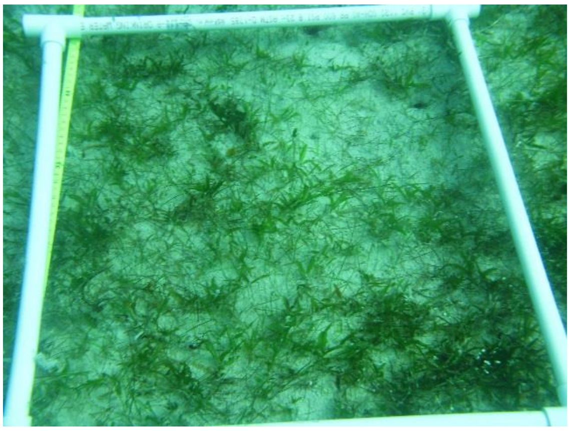
SOURCE: Abu Dhabi Blue Carbon Project

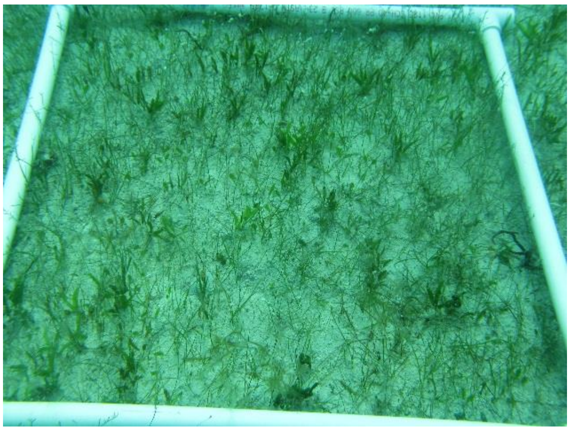
Abu Dhabi Blue Carbon Project

Figure 19D

Carbon density profile of seagrass soil at Umm Al Hatam (error bars = ±1 Std).





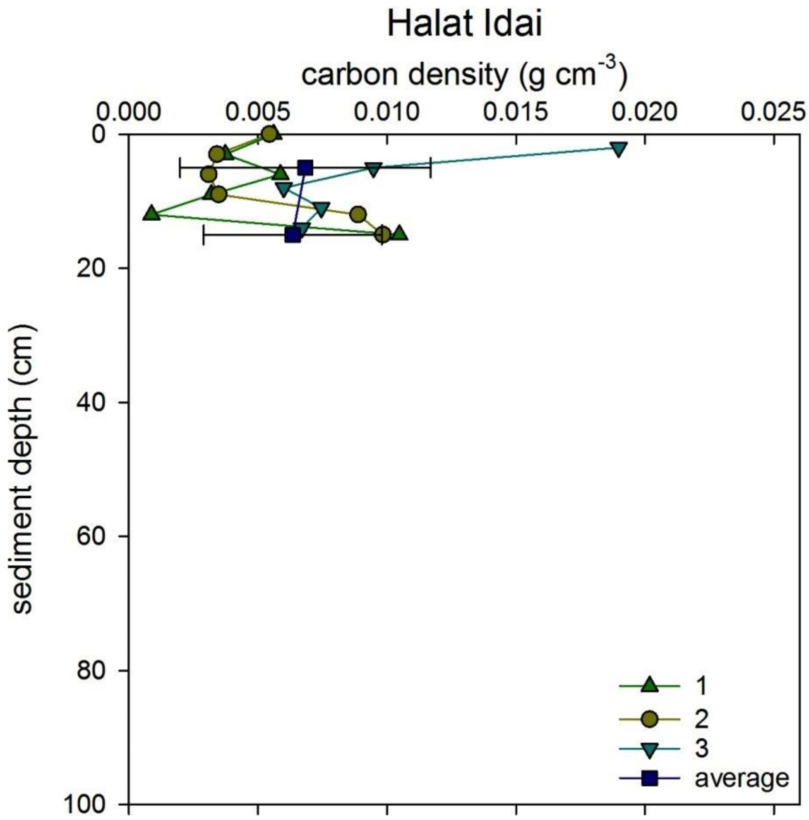


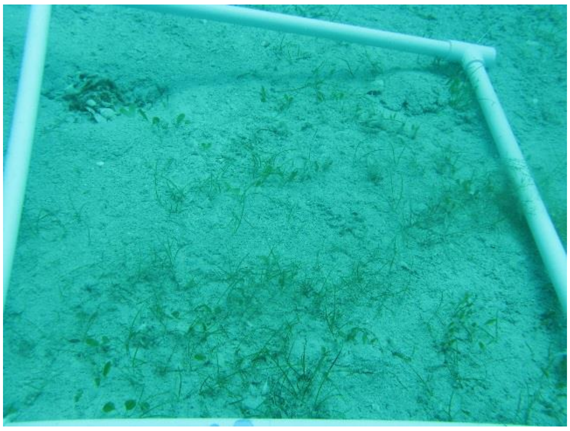
SOURCE: Abu Dhabi Blue Carbon Project

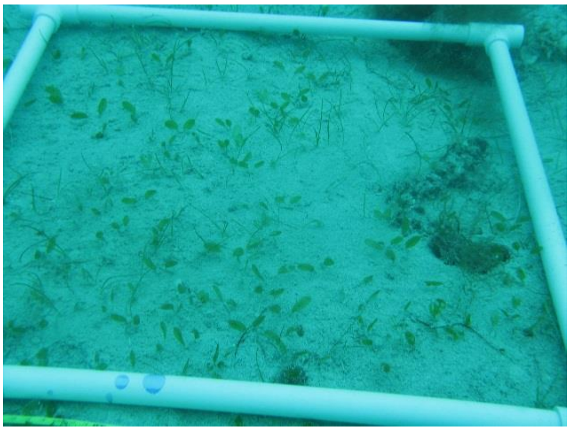
Abu Dhabi Blue Carbon Project

Figure 19E

Carbon density profile of seagrass soil at Jazirat (error bars = ±1 Std).





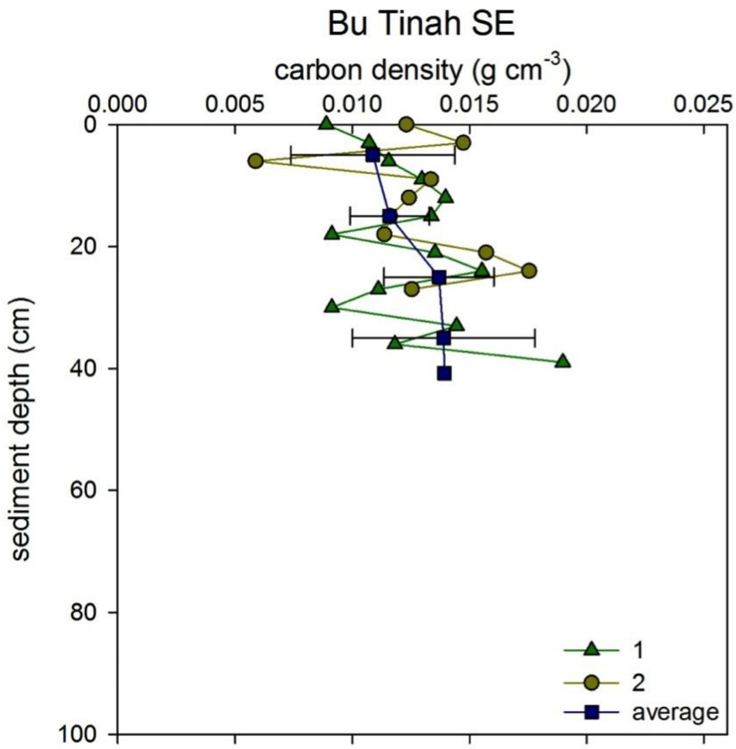


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19F

Carbon density profile of seagrass soil at Halat Idai (error bars = ±1 Std).

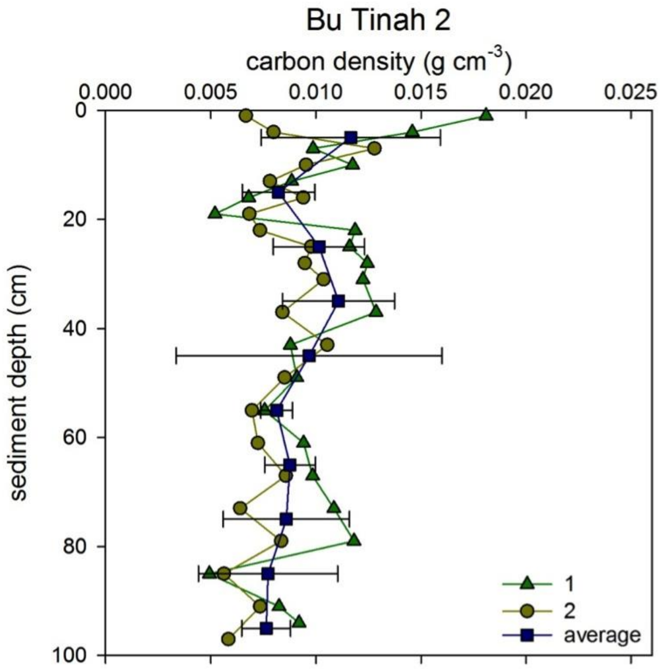


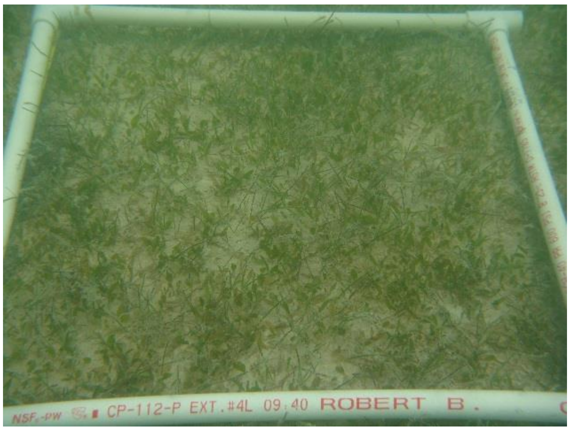
SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19G

Carbon density profile of seagrass soil at Bu Tinah SE (error bars = ±1 Std).



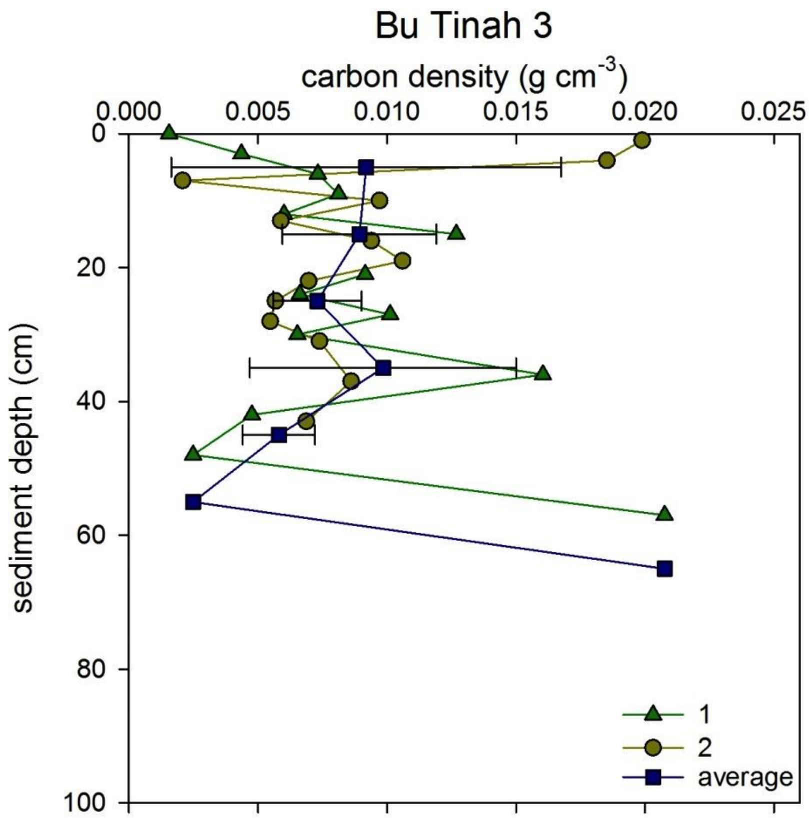


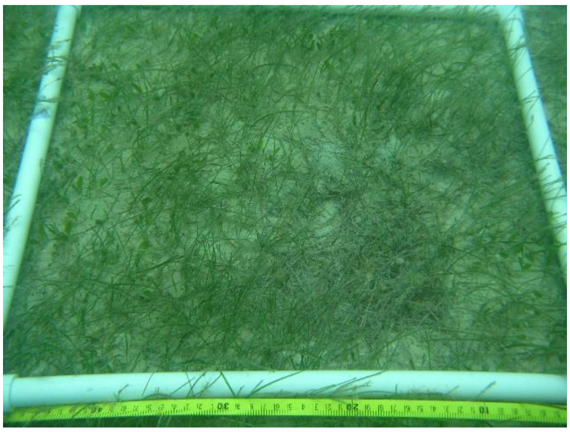
SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19H

Carbon density profile of seagrass soil at Bu Tinah 2 (error bars = ±1 Std).



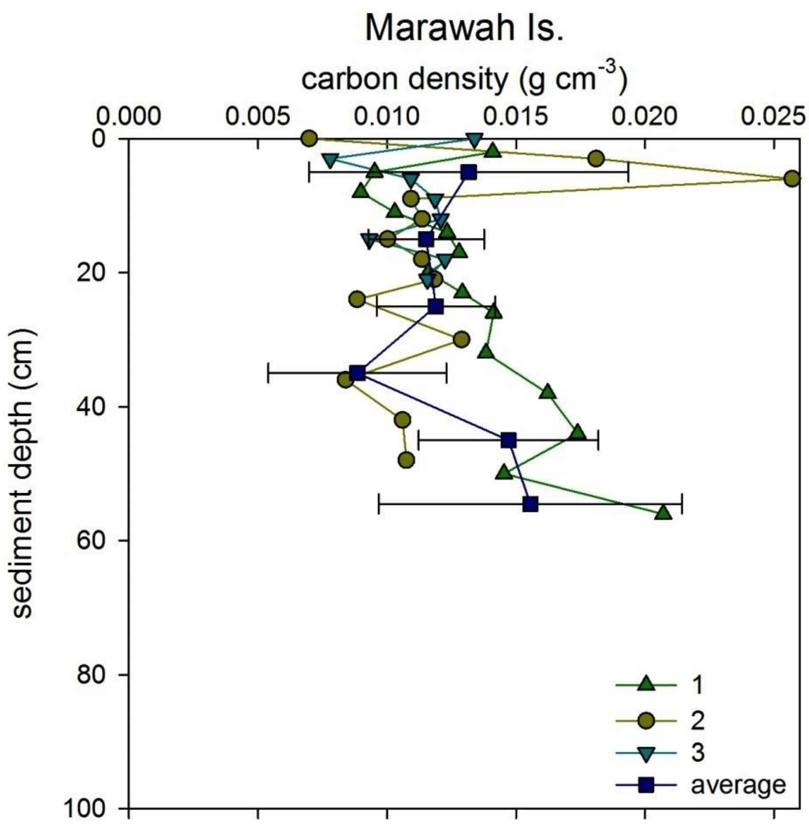


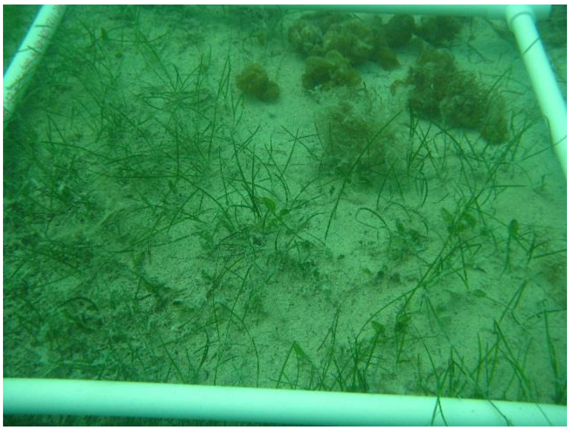
SOURCE: Abu Dhabi Blue Carbon Project

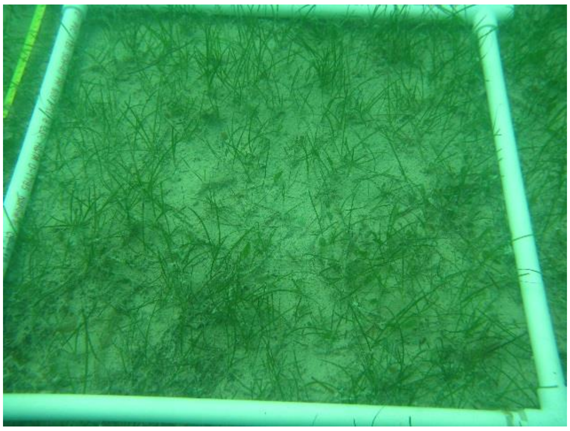
Abu Dhabi Blue Carbon Project

Figure 19I

Carbon density profile of seagrass soil at Bu Tinah 3 (error bars = ±1 Std).

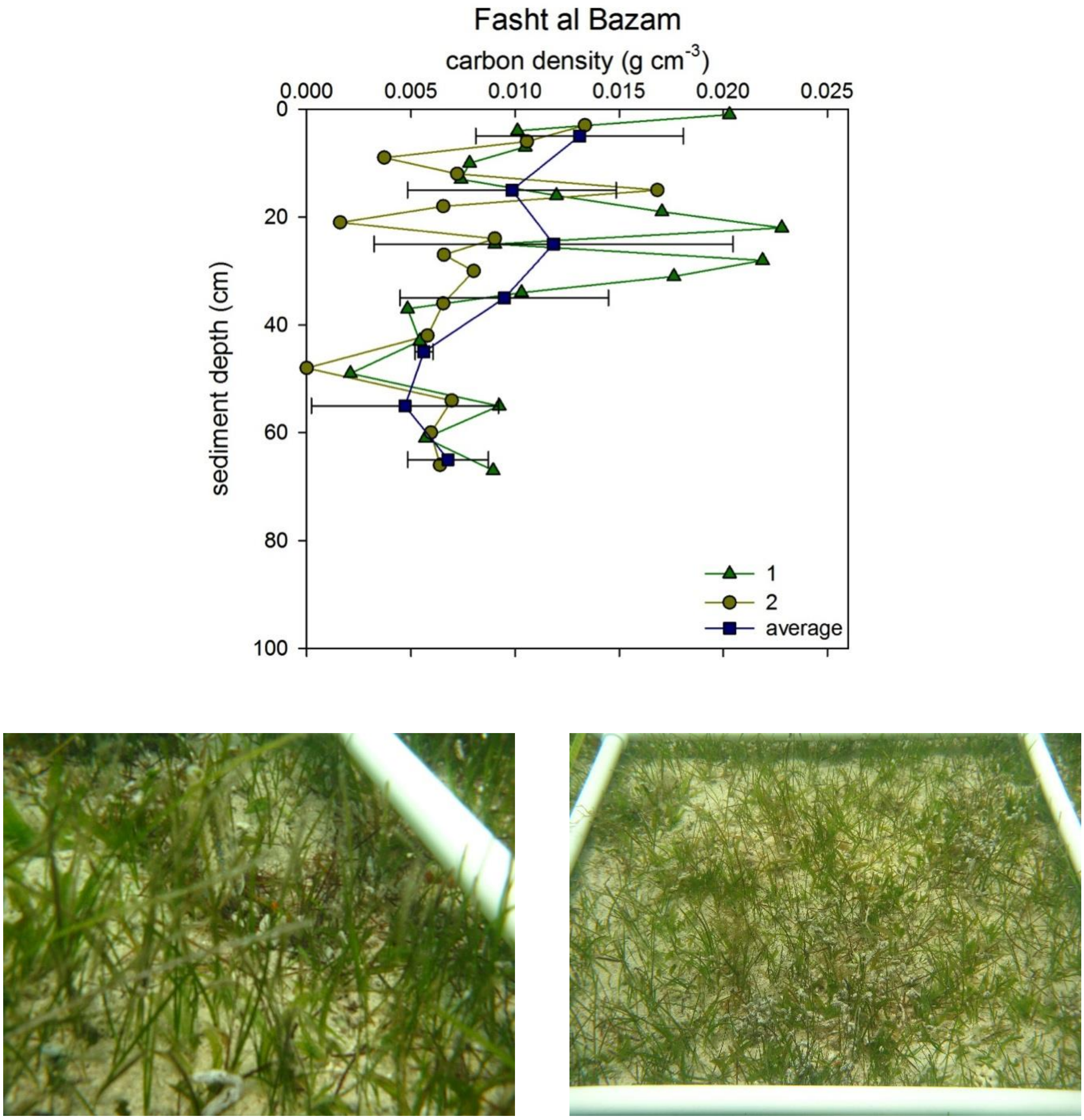






SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project
Figure 19J
Carbon density profile of seagrass soil at Marawah (error bars = ±1 Std).

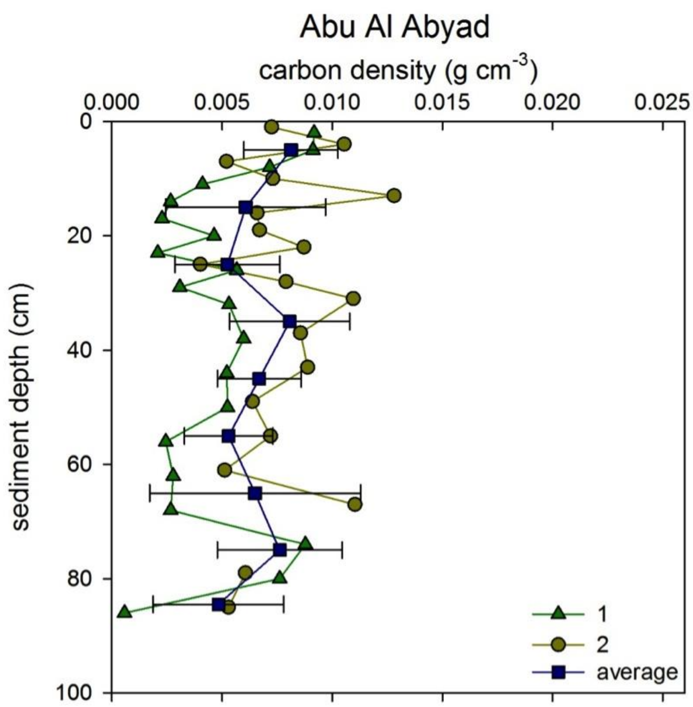


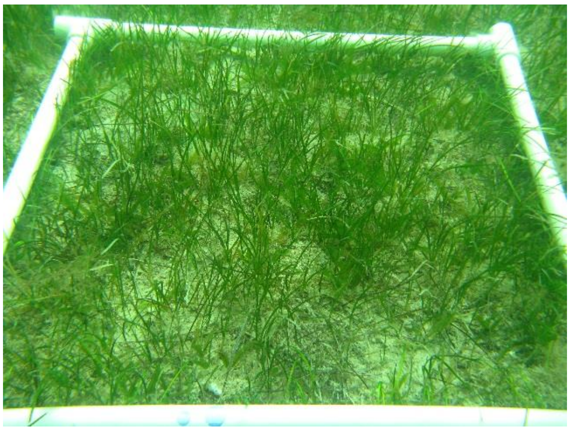
SOURCE: Abu Dhabi Blue Carbon Project

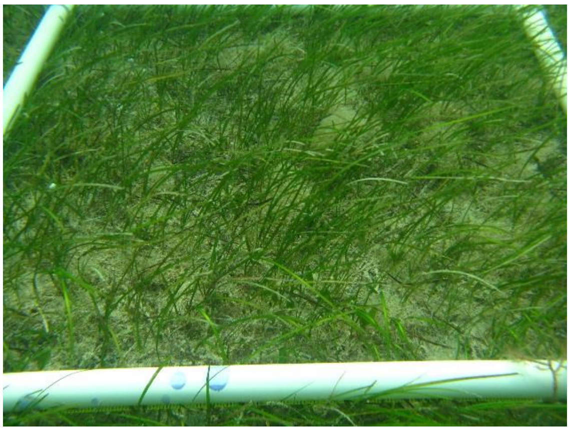
Abu Dhabi Blue Carbon Project

Figure 19K

Carbon density profile of seagrass soil at Fasht al Bazam (error bars = ±1 Std).





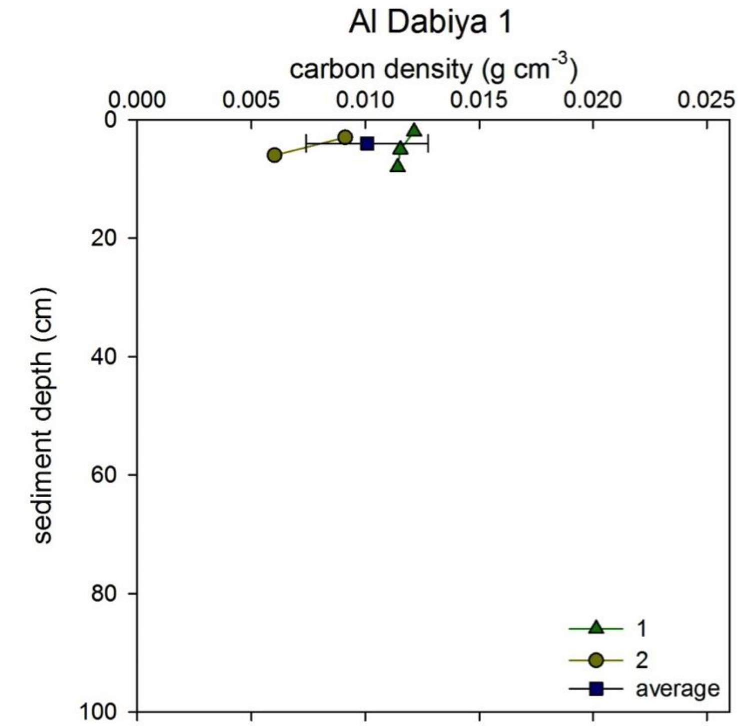


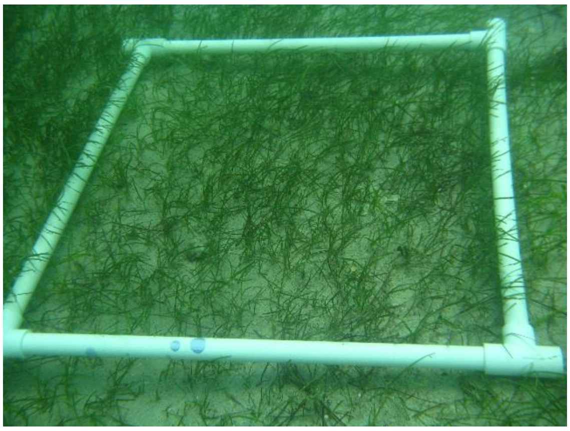
SOURCE: Abu Dhabi Blue Carbon Project

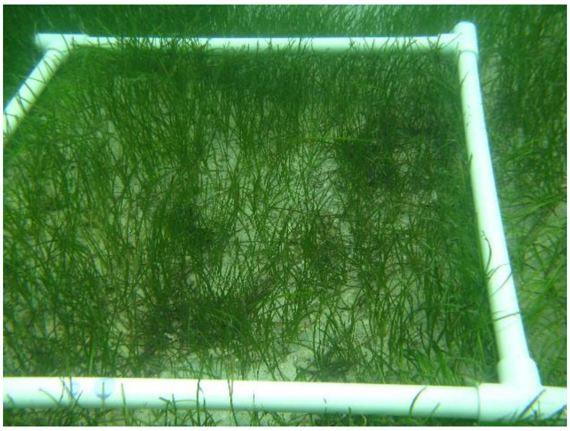
Abu Dhabi Blue Carbon Project

Figure 19L

Carbon density profile of seagrass soil at Abu Al Abyad (error bars = ±1 Std).





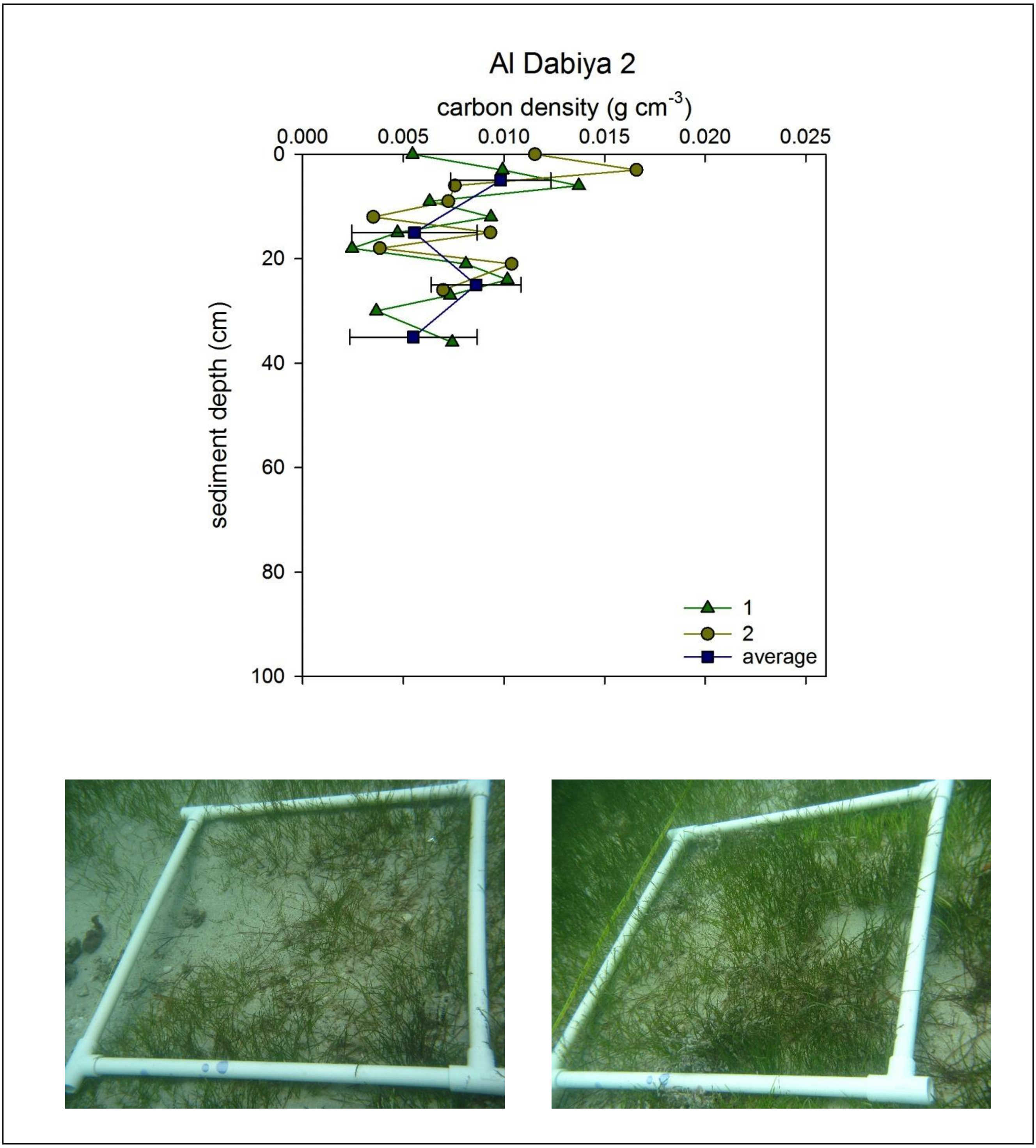


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19M

Carbon density profile of seagrass soil at Al Dabiya 1 (error bars = ±1 Std).

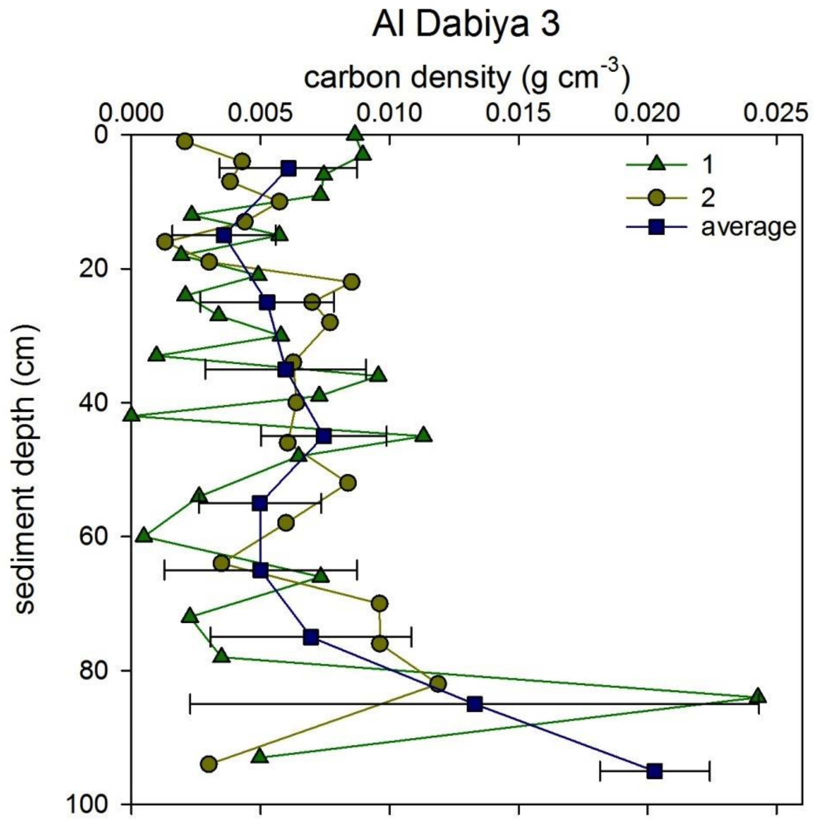


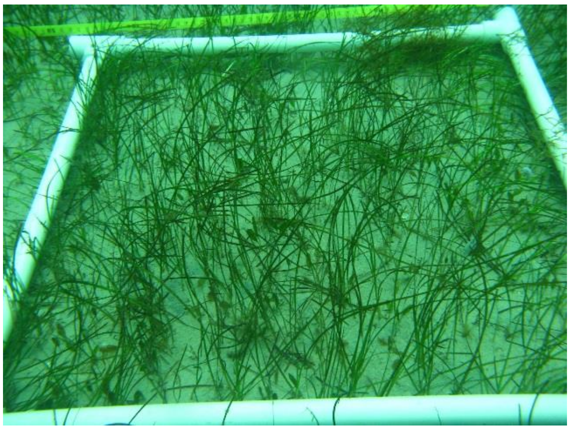
SOURCE: Abu Dhabi Blue Carbon Project

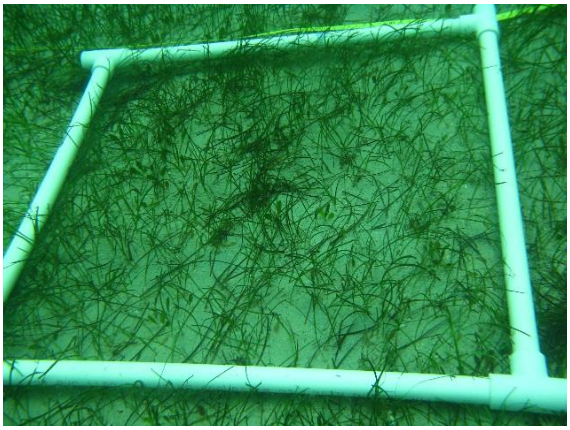
Abu Dhabi Blue Carbon Project

Figure 19N

Carbon density profile of seagrass soil at Al Dabiya 2 (error bars = ±1 Std).





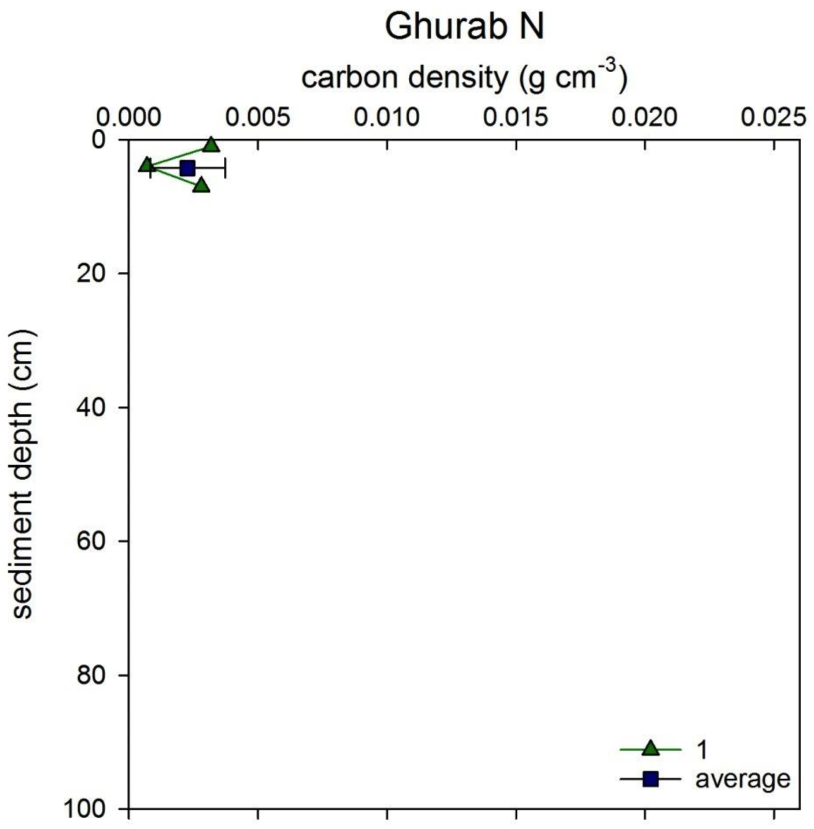


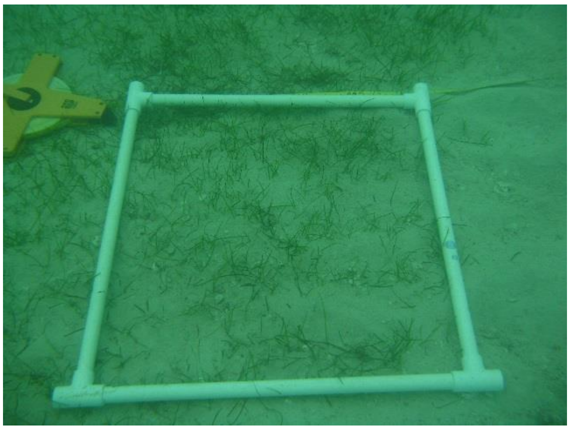
SOURCE: Abu Dhabi Blue Carbon Project

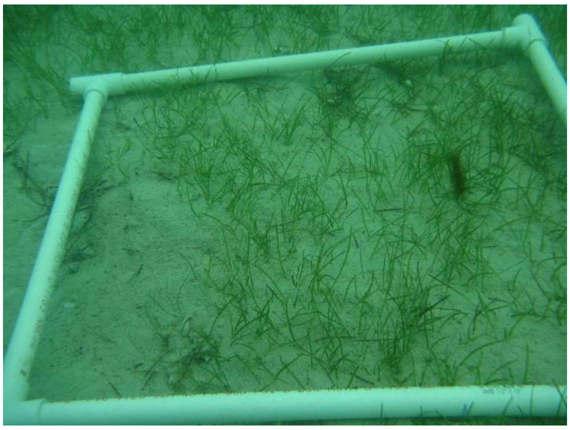
Abu Dhabi Blue Carbon Project

Figure 19O

Carbon density profile of seagrass soil at Al Dabiya 3 (error bars = ±1 Std).





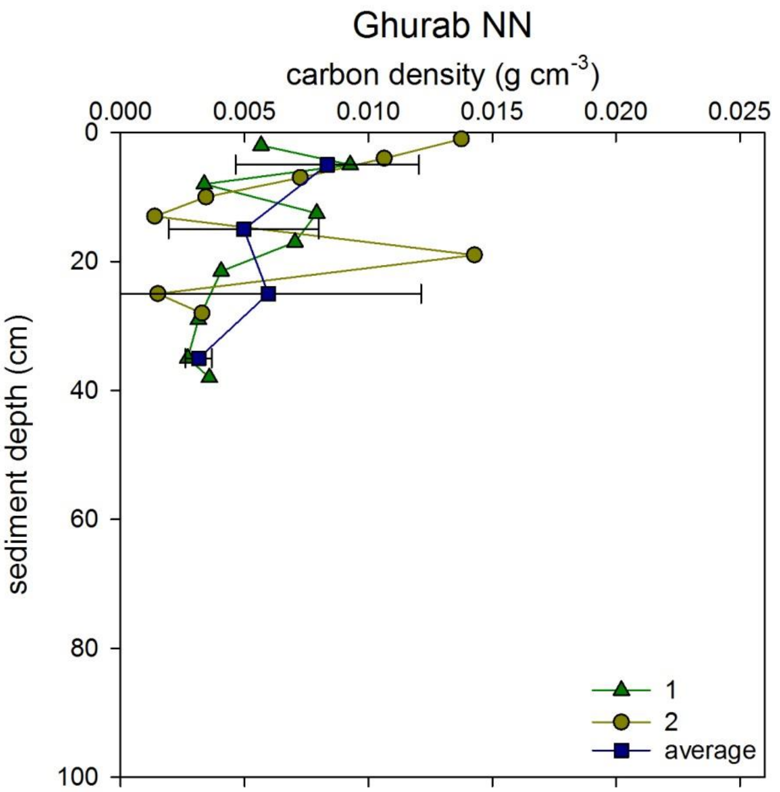


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19P

Carbon density profile of seagrass soil at Ghurab N (error bars = ±1 Std).

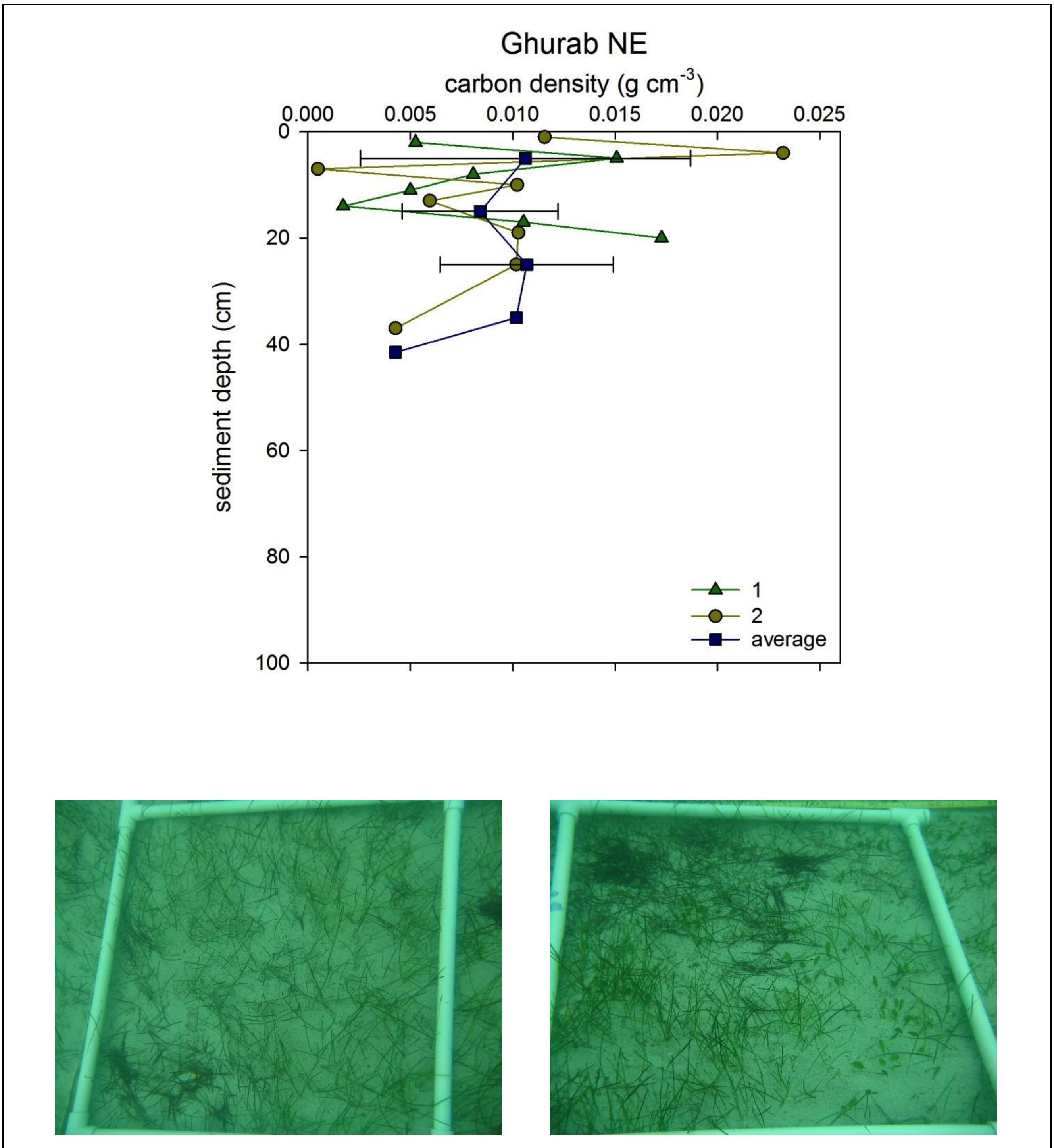


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19Q

Carbon density profile of seagrass soil at Ghurab NN (error bars = ±1 Std).

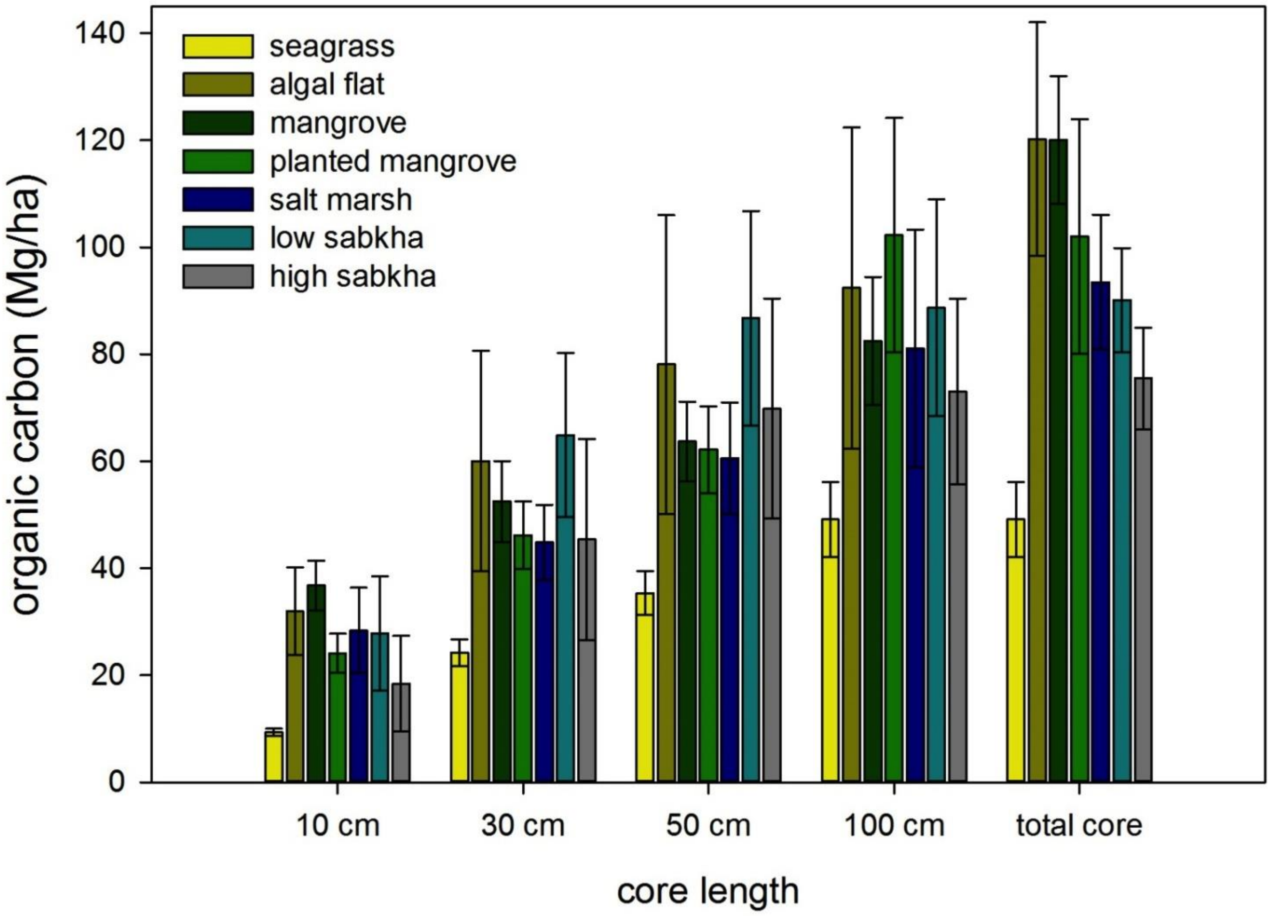


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 19R

Carbon density profile of seagrass soil at Ghurab NE (error bars = ±1 Std).

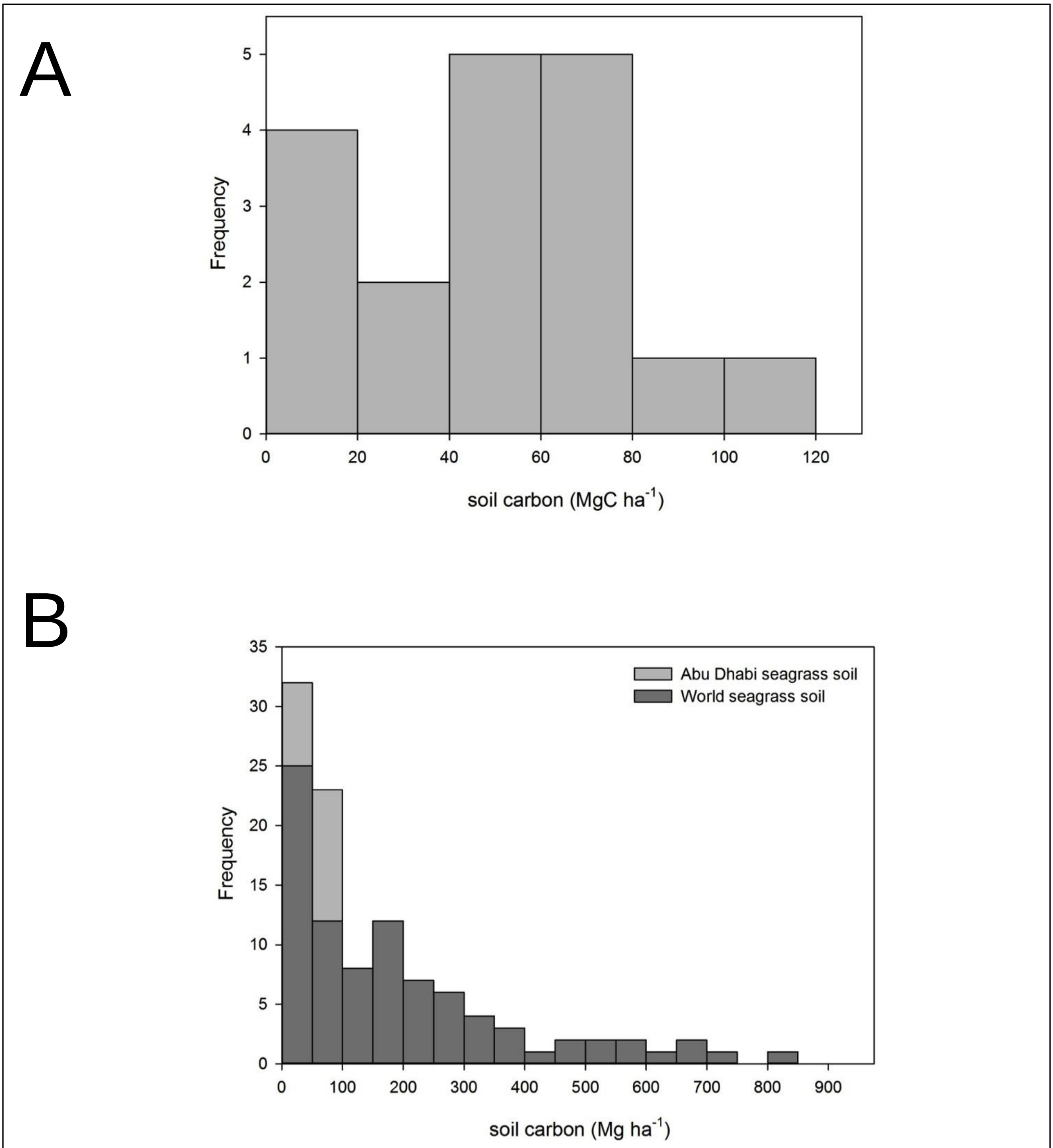


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 20

Soil organic carbon averaged within the top 10, 30, 50, 100cm, and total core length (error bars = ±1 Std).



SOURCE: Abu Dhabi Blue Carbon Project; Fourqurean et al. 2012

Abu Dhabi Blue Carbon Project

Figure 21

Seagrass soil carbon stock in top 100 cm for a) Abu Dhabi soils and b) world and Abu Dhabi soils.

5.2 Plant Carbon Stocks

5.2.1 Mature Mangroves and Salt Marshes

In mature mangrove ecosystems, above- and below-ground biomass varied widely by location (Table 7; Figure 22). The largest average above-ground biomass, 189.1 Mg ha^{-1}, was measured at Bu Tinah and the average lowest biomass, 9.27 Mg ha^{-1}, was found on Jubail Island; the same pattern occurred with total biomass. There was more variation in above-ground biomass than below-ground biomass (Figure 22). Variations in biomass resulted from either differences in tree size (Figure 23a), as seen with Bu Tinah and Jubail Island, or differences in tree density (Figure 23b). The mature sampled stands of Bu Tinah and Salaam (Eastern Mangroves) were the most structurally diverse stands, having the largest crown area and the highest seedling densities (Table 8; Figure 23a). Tree density was greatest at the Eastern Mangrove sites (Eastern Mangrove and Salaam; Figure 23b), where tree density at Salaam exceeded 8000 tree ha^{-1}. Basal area greatly varied among the mangroves by over 10-fold. The mostly open canopy of Jubail Island had the lowest areas while the dense and mature Bu Tinah sites were highest, ranging from 8 – 15 m^2 ha^{-1} (Figure 23). Overall, there was a general trend of stands in the Eastern Mangrove having larger trees in greater density and stands on Jubail Island having fewer trees with smaller canopies. Seedling density was fairly consistent across sites, averaging 10,000 individuals ha^{-1}, yet densities were double (Bu Tinah) or triple (Salaam) (Figure 23b).

In *A. macrostachyum* dominated salt marshes, above-ground biomass was mostly consistent across sites, ranging from 2 to 4 Mg ha^{-1} (Figure 24). The Eastern Mangrove site amassed more than double the biomass of any other site (Figure 24). No data on below-ground biomass were collected, nor were root to shoot ratios available in the literature for this species or congeners.

5.2.2 Planted Mangroves

Above- and below-ground biomass of planted mangroves varied with stand age and location (Table 9; Figure 25). Plant biomass and structure increased with stand age, going from 0.8 to 10.9 and 0.05 to 5.8 Mg ha^{-1} at Jubail Island and Abu Al Abyad, respectively. Stands on Jubail Island had greater biomass than those on Abu Al Abyad across all ages; plantations aged 10 years were twice as large and stands aged 3 years were 16 times as large. Yearly carbon sequestration in total plant biomass increased with stand age, quadrupling from youngest to oldest stands on both islands, but did not differ between older stands within a site (Figure 25b). Rates were the greatest for older stands on Jubail Island and were nearly three times greater than the oldest stands on Abu Al Abyad (Figure 25b). The oldest planted mangrove, aged 15 years at Abu Al Abyad, had a surprising number of seedlings (42,017 ± 12,223 seedlings ha^{-1}), which was on par with the highest density measured in mature mangroves (Table 8; Figure 23b). Surveyed elevations at Abu Al Abyad were much lower in the tidal frame than those at Jubail Island (Figure 26), although uncorrected elevations did not differ (Figure 25).

Table 7 Summary of mature mangrove biomass and soil carbon storage in the top 1m

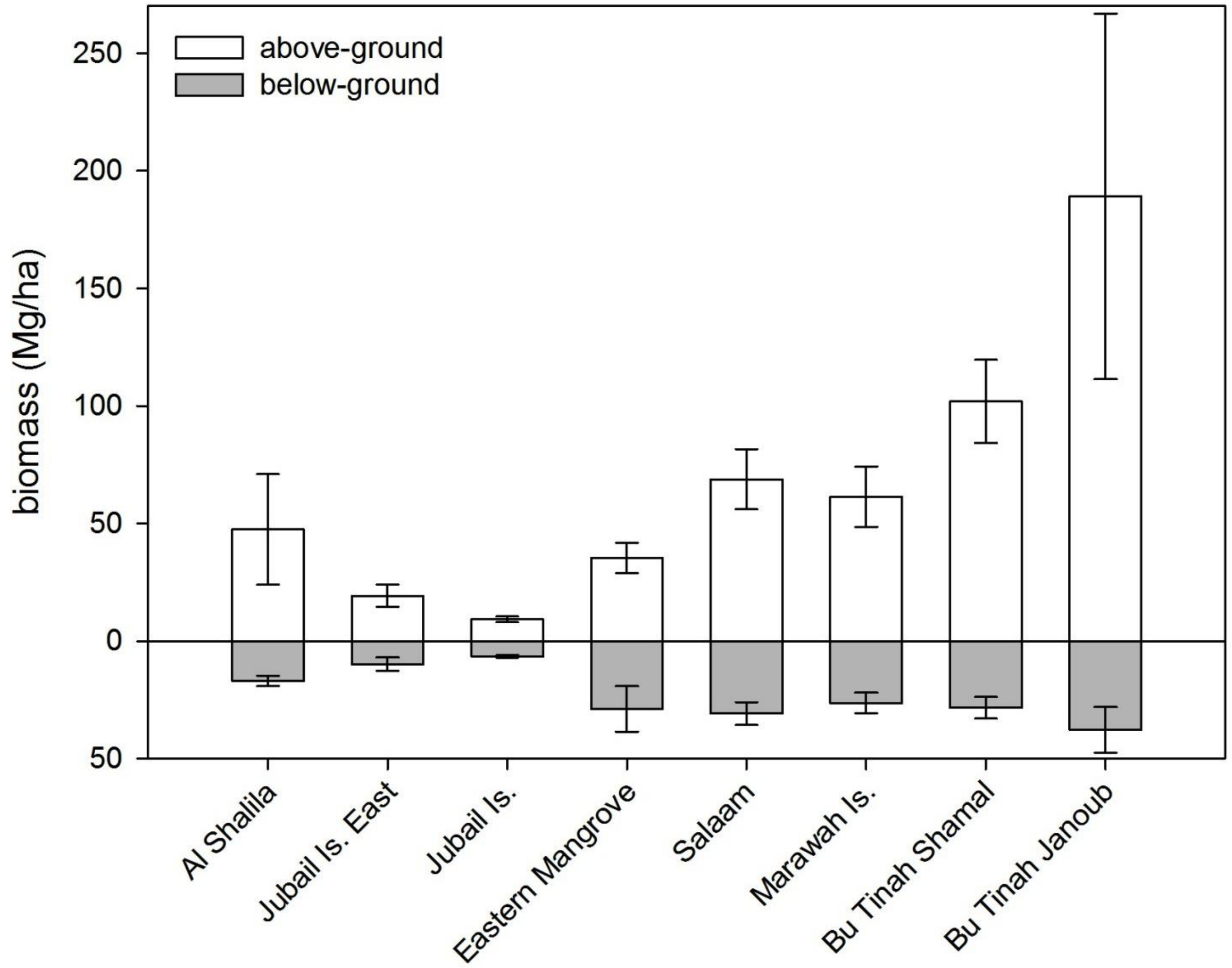
	Tree biomass (Mg ha^{-1})		
Site	Above-ground	Below-ground	C (Mg ha^{-1})
Al Shalila	47.49 ± 23.52	16.91 ± 2.2	30.91 ± 12.03
Jubail Is. East	19.3 ± 4.71	9.86 ± 2.88	13.99 ± 3.61
Jubail Is.	9.27 ± 1.21	6.48 ± 0.55	7.56 ± 0.58
Eastern Mangrove	35.30 ± 6.41	28.88 ± 9.62	30.81 ± 7.65
Salaam	68.81 ± 12.75	30.83 ± 4.87	47.83 ± 8.21
Marawah Is.	61.42 ± 12.86	26.35 ± 4.41	42.13 ± 8.27
Bu Tinah Shamal	101.91 ± 17.7	28.37 ± 4.59	62.54 ± 10.45
Bu Tinah Janoub	189.14 ± 77.79	37.77 ± 9.71	122.29 ± 33.03

Table 8 Summary of tree characteristics in mature mangrove ecosystems

Site	Seedling Density (ha^{-1})	Tree Density (ha^{-1})	Crown Area (m^2 ha^{-1})	Basal Area (m^2 ha^{-1})
Al Shalila	17904.9 ± 7081.2	4227.9 ± 637.2	10868.1 ± 613.2	3.9 ± 1.4
Jubail Is. East	9284.0 ± 6408.1	2384.6 ± 850.5	9022.1 ± 2043.1	1.9 ± 0.5
Jubail Is.	nd	2955.7 ± 401.4	3685.1 ± 1332.7	0.6 ± 0.2
Eastern Mangrove	10345.1 ± 3431.9	10734.8 ± 4520.9	11712.0 ± 1008.2	4.3 ± 0.9
Salaam	34218.3 ± 11465.8	9459.9 ± 2329.6	19871.0 ± 3546.8	6.7 ± 1.3
Marawah Is.	6631.5 ± 1845.4	4604.1 ±647.1	nd	6.1 ± 1.2
Bu Tinah Shamal	17904.9 ± 7081.2	3001.8 ± 637.5	46097.8	9.0 ± 1.5
Bu Tinah Janoub	14058.7 ± 3544.9	1886.6 ± 519.4	17814.6 ± 4892.8	1.4 ± 5.6

Table 9 Summary tree characteristics and carbon stocks of planted mangroves

				Tree biomass (Mg ha^{-1})		
Site	**Density (ha^{-1})**	**Crown Area (m^2 ha^{-1})**	**Basal Area (m^2 ha^{-1})**	**Above-ground**	**Below-ground**	**C (Mg ha^{-1})**
Eastern Mangrove 3 yr	5570.4 ± 435.9	389.9 ± 42.3	0.3 ± 0.04	0.8 ± 0.1	0.7 ± 0.1	0.7 ± 0.1
Eastern Mangrove 7 yr	4933.8 ± 464.0	5389.6 ± 906.5	2.7 ± 0.4	7.7 ± 1.2	7.2 ± 1.1	6.5 ± 1.1
Eastern Mangrove 10 yr	28488.7 ± 4781.3	7006.3 ± 1544.7	3.8 ± 0.9	10.9 ± 2.5	10.1 ± 2.3	9.2 ± 2.3
Abu Al Abyad 3 yr	625.0	15.9 ± 1.4	0.02 ± 0.002	0.05 ± 0.004	0.05 ± 0.004	0.04 ± 0.004
Abu Al Abyad 5 yr	830.7	139.4 ± 14.4	0.2 ± 0.02	0.4 ± 0.06	0.4 ± 0.1	0.4 ± 0.1
Abu Al Abyad 10 yr	1463.9	934.3 ± 102.5	1.4 ± 0.2	4.1 ± 0.5	3.8 ± 0.5	3.5 ± 0.5
Abu Al Abyad 15 yr	889.9 ± 424.2	4458.2 ± 1017.7	1.9 ± 0.4	5.8 ± 1.2	5.4 ± 1.1	no data

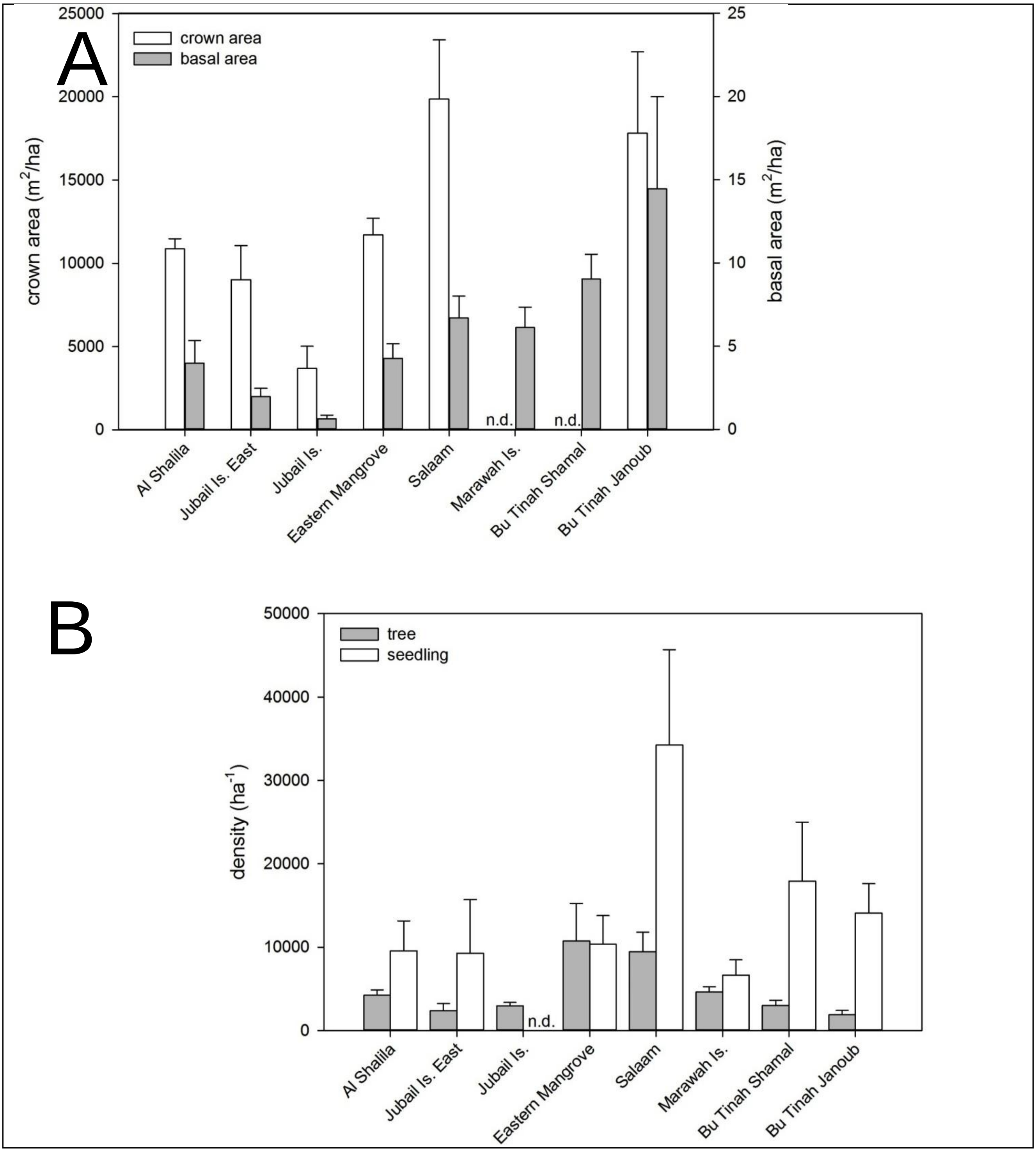


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 22

Above- and below-ground biomass of *A. marina* trees in mature forests (nd = no data; error bars = ±1 SE).

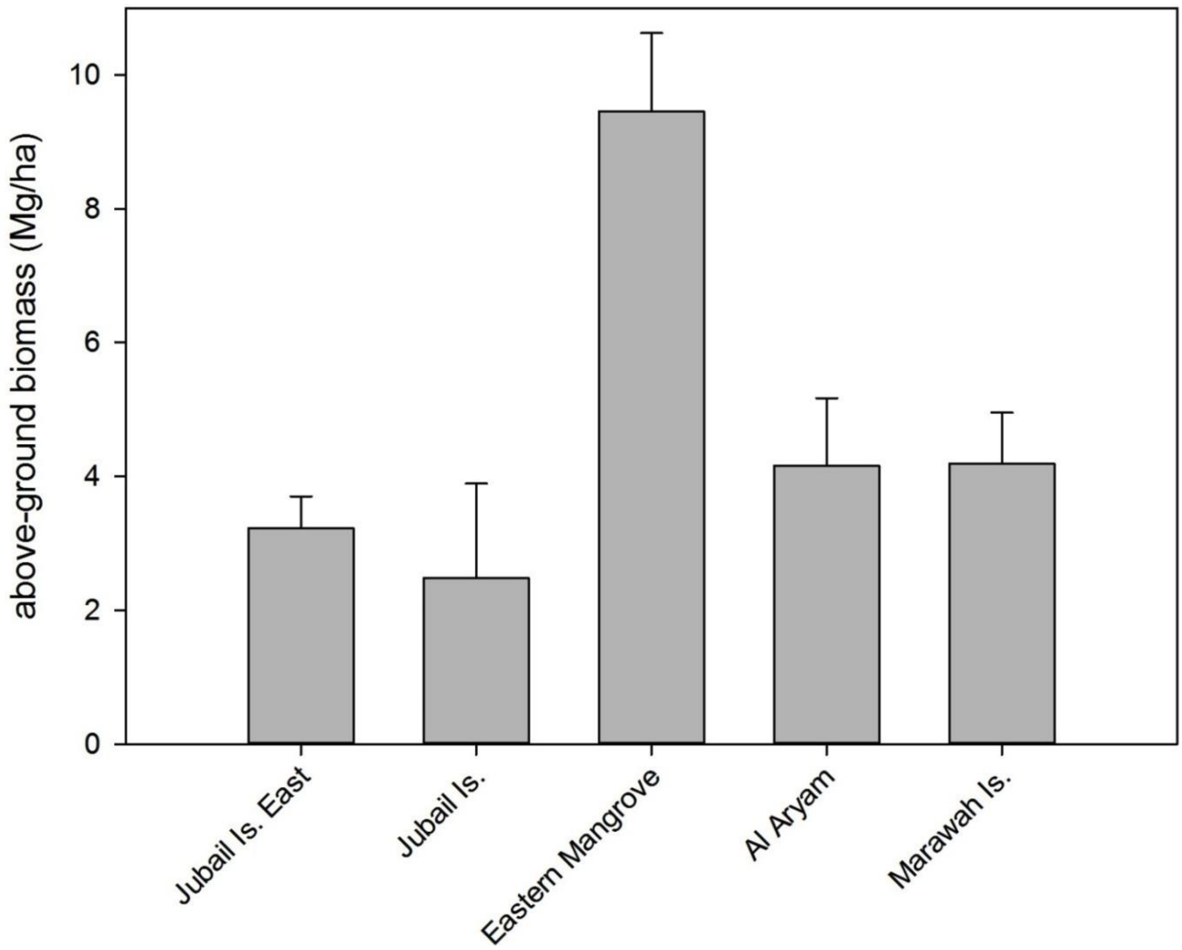


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 23

a) Crown & basal area & b) density of *A. marina* trees and seedlings (nd = no data; error bars = ±1 SE).

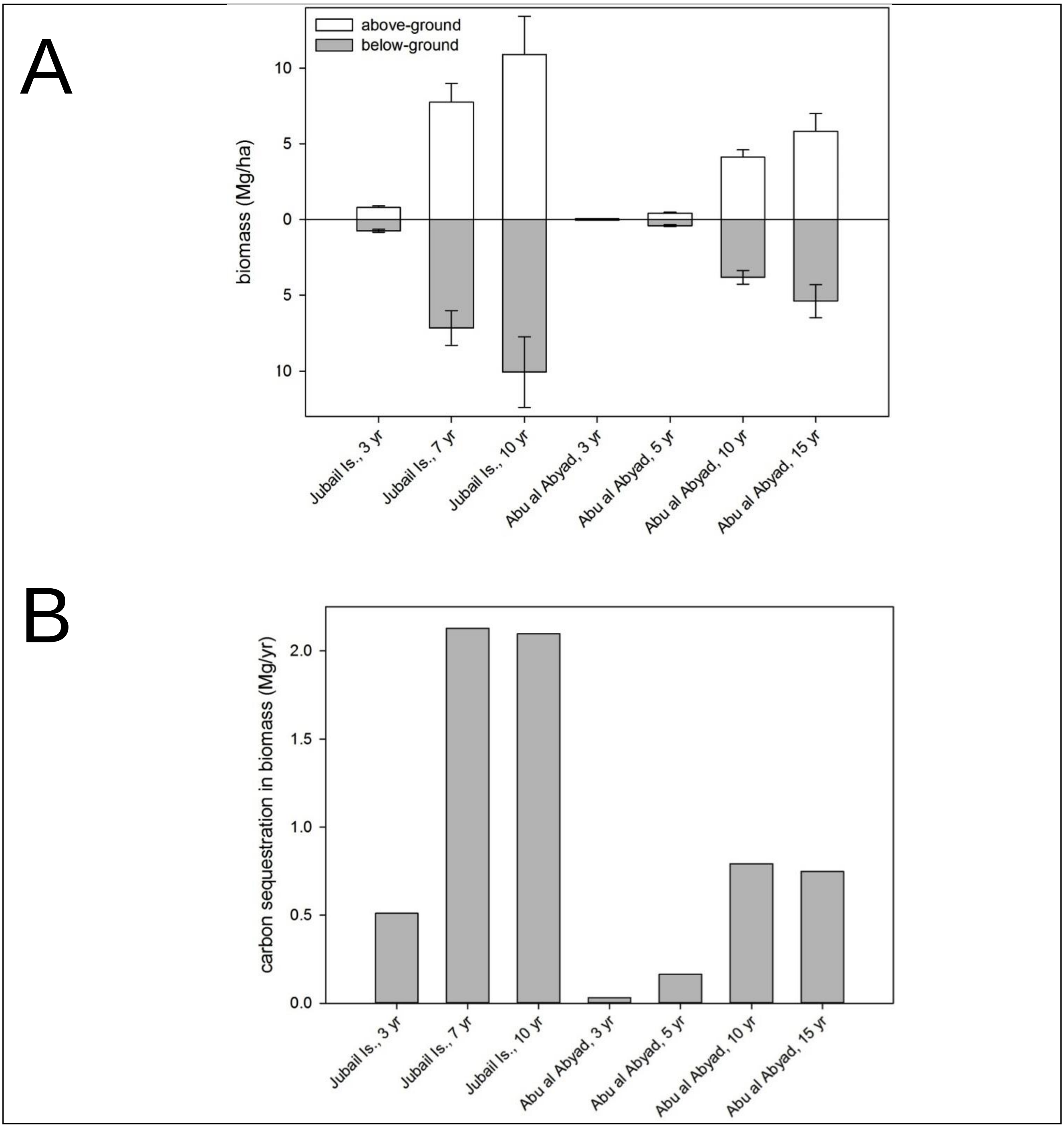


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 24

Above-ground biomass of *A. macrostachyum* in salt marshes (error bars = ±1 SE).



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 25

a) Above- and below-ground biomass and b) average yearly carbon sequestration of *A. marina* trees in planted forests.

5.2.3 Seagrass Beds

All surveyed sites supported seagrasses. Three species of seagrass were encountered: *Halodule uninervis* (Forsskäl) Ascherson), *Halophila ovalis* (Brown) and *Halophila stipulacea* (Forsskäl) Ascherson) (Figure 2e-f).

Seagrass abundance, as assessed by percent cover, ranged from a low of 7.5% at the Sila Peninsula and Halat Idai sites to a high of 86.9% at Abu al Abyad (Table 10). *Halodule uninervis* was the most commonly encountered seagrass; it was present at all 18 survey sites. *Halophila ovalis* was absent from one of the 18 sites, while its congener *H. stipulacea* was only found at 11 of the 18 sites. Notably, *H. stipulacea* was absent from the easternmost sample area. Despite its common distribution, *H. ovalis* was never found in high abundance; it never exceeded 10% cover. Carbon stored in the seagrass biomass of Abu Dhabi seagrass beds was relatively modest; these stores ranged from 0.03 to 1.13 MgC ha^{-1} with a mean of 0.4 ± 0.1 (± 1 standard error; Table 10).

There was no significant relationship between the abundance of seagrasses, as assessed either as percent cover or living plant biomass, with soil carbon stores. This is likely a result of the very broad area of subtidal soils in the coastal zone that support ephemeral seagrass patches that move across the surface of the soils as they expand at one end and erode away at the other end.

5.3 Total Carbon Stocks

The greatest above-ground carbon pools were measured in the mature mangrove ecosystems (Table 11; Figures 28-30), where biomass ranged from 4 to 90 Mg C ha^{-1}. The older planted mangroves had comparable above-ground carbon storage to the salt marshes, averaging 1.9 Mg C ha^{-1}. Total seagrass biomass varied between 0.3 and 1.1 Mg C ha-1 (Table 10), which is lowest out of all sampled ecosystems. Within the top 100cm of soil, total carbon pools appeared to be the highest in mature mangrove ecosystems, although sample sizes were not consistent across ecosystems and differences are not statistically different (Figure 31). Planted mangroves, salt marshes, algal flats, and coastal sabkha were comparable in their storage, ranging from 82 to 105 MgC ha^{-1}; seagrasses had the lowest total carbon stocks, with approximately 50 MgC ha^{-1} (Table 11; Figure 31).

5.4 In Situ Data

5.4.1 Elevation and tidal data

Comparing sites that were in close proximity to each other, the intertidal ecosystem types tended to separate spatially by elevations as follows (dry to wet): high sabkha > low sabkha > marsh > mature mangrove > planted mangrove > algal flat (Figures 26 & 27). At Jubail Island, salt marshes were located at the highest elevations, followed by the mature and planted mangroves. Similar patterns were seen at the Eastern Mangroves site; however, the mature mangrove at Salaam was close in elevation to the salt marsh. At Al Aryam, there was clear separation across ecosystems, although the salt marsh and low sabkha were close in elevation. Planted mangroves at Abu Al Abyad were very low in elevation compared to the algal flat and low sabkha that were proximately located. The mature mangroves at Bu Tinah were higher in elevation that the mangrove at Marawah Island and similar in elevation to the salt marsh at Marawah Island.

Using differences in land elevation to infer differences in flooding frequency is difficult when the sites are not in close proximity to one another because sea elevation (i.e. sea level) can also vary dramatically across locations. A cross-location comparison of flooding frequency was attempted by normalizing land elevation relative to tide elevation at the closest tide gauge station (Table 12; Figure 27). The result of this analysis suggests that there is local variation in tide elevation that the present network of gauges does not capture. For example, the analysis suggests that high sabkha at Al Aryam occurs at a lower elevation relative to sea level than mangroves at the Eastern Mangroves site. This demonstrates the need for more localized tide elevation data to inform the design of Blue Carbon projects.

5.4.2 Pore-water

Pore-water salinity indicated that the coastal sabkha and algal flat ecosystems were hypersaline with mean salinities of about 150-250 PSU (Figure 32). Salt marshes, mature mangroves, and planted mangroves all had salinities of approximately 50 PSU, with relatively little variation across ecosystems or sites within ecosystems. There was variability in redox potential among ecosystems (Figure 33) that generally reflected differences in elevation. Because ecosystems at high elevation are flooded less often than those at low elevation systems, they are expected to have a greater O_2 supply and therefore relatively high redox potentials. Indeed, redox potential 10 cm below the soil surface was greatest in the coastal sabkha ecosystems and general decreased with increased flooding (i.e. decreased elevation). Algal flats and salt marshes had similar redox potentials, as did mature mangroves and algal flats (Figure 33b). The planted mangroves at Abu Al Abyad had the lowest measured redox potentials, which indicate anaerobic conditions as expected of these sites because of their low elevations and frequent flooding (Figure 26 & 27). Pore-water pH varied from about 7.0 to 8.5, with slightly higher pH in algal flats than in vegetated ecosystems (marsh and mangrove), and lower pH in coastal sabkha (Figure 34b). The sulphate depletion values indicate that the balance of sulphate consumption by anaerobic sulphate-reducing bacteria versus sulphate resupply from flooding is extreme at Thumayriyah (Figure 35c). This observation suggests that hypersaline conditions are primarily a consequence of infrequent resupply of sea water. Pore-water methane concentrations within ecosystems and across sites were generally slightly elevated above ambient atmospheric levels of about 2 ppm (Figure 36). Methane concentrations at the 5 year old planted mangrove at Abu Al Abyad were markedly greater than any other site (Figure 36a), and concentrations were elevated in the Thumayriyah sites were sulphate was most heavily depleted.

5.4.3 Soil Respiration

Soil respiration varied widely within ecosystems, but trends in respiration rates were observed across ecosystems (Figure 37). There was a non-significant, positive relationship between the total ecosystem carbon pool and CO_2 emissions across the intertidal ecosystems (r^2 = 0.28, p = 0.29). The low sabkha sites showed more respiration than expected from the amount of organic carbon in the system; when this ecosystem is removed the r^2 improved to 0.63 (p = 0.11). Respiration was the greatest at the Bu Tinah Janoub mangrove where above- and below-ground biomass was greatest, and lowest in the planted mangroves at Abu Al Abyad (Figure 36a).

The negative fluxes measured in the 5 year-old site for calculating means were not utilised, however, as they were most likely erroneous due to pressure changes in the measurement chamber caused by the outgoing tide. Across ecosystems, soil respiration in the planted mangroves was the lowest, followed by high sabkha (Figure 37b). Rates did not vary greatly between algal flats and salt marshes, and mature mangroves and low sabkha habitats had the greatest respiration rates (Figure 37b).

Table 10 Summary of seagrass cover and biomass by species

Site name	Seagrass canopy height (cm)	*Halodule uninervis (% cover)*	*Halophila ovalis (% cover)*	*Halophila stipulacea (% cover)*	Total seagrass (% cover)	Total seagrass biomass (MgC ha^{-1})
Ras Muhayjij	5.9	2.5	2.5	62.5	67.5	0.37
Dahwat an Nahklah	7.4	8.4	4.7	4.7	17.7	0.09
Sila peninsula	5.0	2.5	2.5	2.5	7.5	0.05
Umm Al Hatam	8.5	47.5	2.5	2.5	52.5	0.35
Jazirat	8.7	18.9	2.5	9.9	31.3	0.72
Halat Idai	7.9	2.5	2.5	2.5	7.5	0.03
Bu Tinah 3	6.9	19.8	6.8	5.8	32.4	0.49
Bu Tinah 2	7.6	17.3	7.4	36.5	61.2	0.49
Bu Tinah SE	6.3	6.4	9.3	0.0	15.7	0.13
Marawah	8.0	11.3	2.5	2.5	16.3	0.12
Fasht al Bazam	9.0	24.9	2.5	8.4	35.7	0.82
Abu al Abyab	17.9	60.0	6.7	20.2	86.9	0.73
Al Dabiya1	7.4	41.4	2.5	0.0	43.9	0.83
Al Dabiya2	8.4	65.0	2.5	0.0	67.5	1.13
Al Dabiya3	10.8	50.0	3.5	0.0	53.5	0.40
Ghurab N	5.0	22.4	2.5	0.0	24.9	0.17
Ghurab NN	6.8	8.1	0.0	0.0	8.1	0.21
Ghurab NE	8.2	17.3	4.9	0.0	22.2	0.43
Mean	8.1	23.7	3.8	8.8	36.2	0.4
SE of the Mean	0.7	4.8	0.6	3.8	5.6	0.1
Median	7.8	18.1	2.5	2.5	31.8	0.4
Min	5.0	2.5	0.0	0.0	7.5	0.0
Max	17.9	65.0	9.3	62.5	86.9	1.1

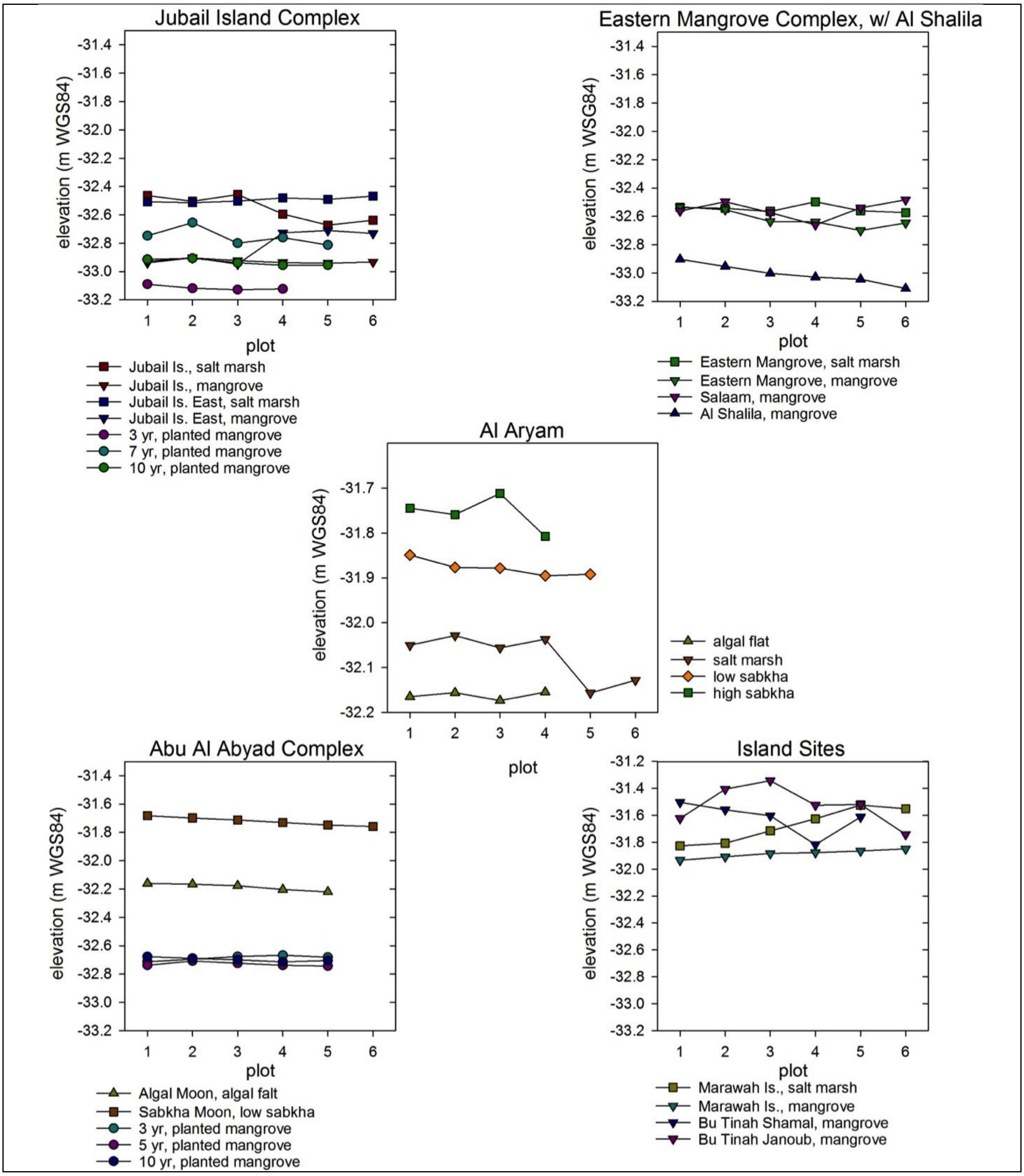
Table 11 Summary of carbon stock in intertidal ecosystems

C (Mg ha^{-1})		Seagrass	Algal flat	Mature mangrove	Planted mangrove	Salt marsh	Coastal sabkha
Soil[a]	range	1.9 - 109.0	18.6 - 153.3	36.7 – 155.3	50.9 – 175.8	29.5 - 163.7	51.0 - 120.5
	mean	49.1	96.3	102.3	102.3	80.4	86.1
	median	51.2	106.5	87.8	87.8	71.1	94.6
Above-ground biomass	range	no data	N/A	4.4 - 90.8	0.02 - 5.2	0.9 - 3.8	N/A
	mean	no data	N/A	32	1.9	1.9	N/A
	median	no data	N/A	26.1	1.2	1.7	N/A
Below-ground biomass	range	no data	N/A	2.5 – 12.1	0.02 - 3.9	no data	N/A
	mean	no data	N/A	8.7	1.4	no data	N/A
	median	no data	N/A	10.7	0.9	no data	N/A
Total plant biomass	range	0.3 - 1.1	N/A	7.0 – 102.9	0.04 - 9.2	no data	N/A
	mean	0.4	N/A	40.7	3.4	no data	N/A
	median	0.4	N/A	34.6	2.1	no data	N/A
Below-ground stock	range	1.9 - 109.0[b]	18.6 - 153.3	48.8 – 165.4	52.4 – 178.6	29.5 - 163.7[b]	51.0 - 120.5
	mean	49.1[b]	96.3	91.2	103.7	80.4[b]	86.1
	median	51.2[b]	106.5	83.9	87.9	71.1[b]	94.6
Total carbon stock	range	2.2 - 109.3	18.6 - 153.3	77.9 – 198.4	54.4 - 182.3	30.5 - 165.4[b]	51.0 - 120.5
	mean	49.6	96.3	123.1	105.6	82.3[b]	86.1
	median	51.6	106.5	123.3	88.1	72.4[b]	94.6

[a] = data restricted to top 100cm of soil; [b] = totals do not include below-ground biomass

Table 12 Tidal metrics calculated for tide stations close to sampling locations

Tide station	Corresponding Site	MHW	MLW	MTL	MHW - MTL
Abu Al Abyad (4213)	Abu al Abyad, Sabkha Moon, Algal Moon, Rafiq	1.917	0.903	1.410	0.507
Ras Zubayyah (4212)	Al Aryam	1.701	0.857	1.279	0.422
Khawr Ghanadah (4208)	Al Shalila	1.360	0.484	0.922	0.437
Umm An Nar (4210D)	Eastern Mangroves, Jubail Is.	1.186	0.591	0.889	0.298
Fasht Al Bazam (4213A)	Marawah Is., Bu Tinah	1.823	1.019	1.421	0.402

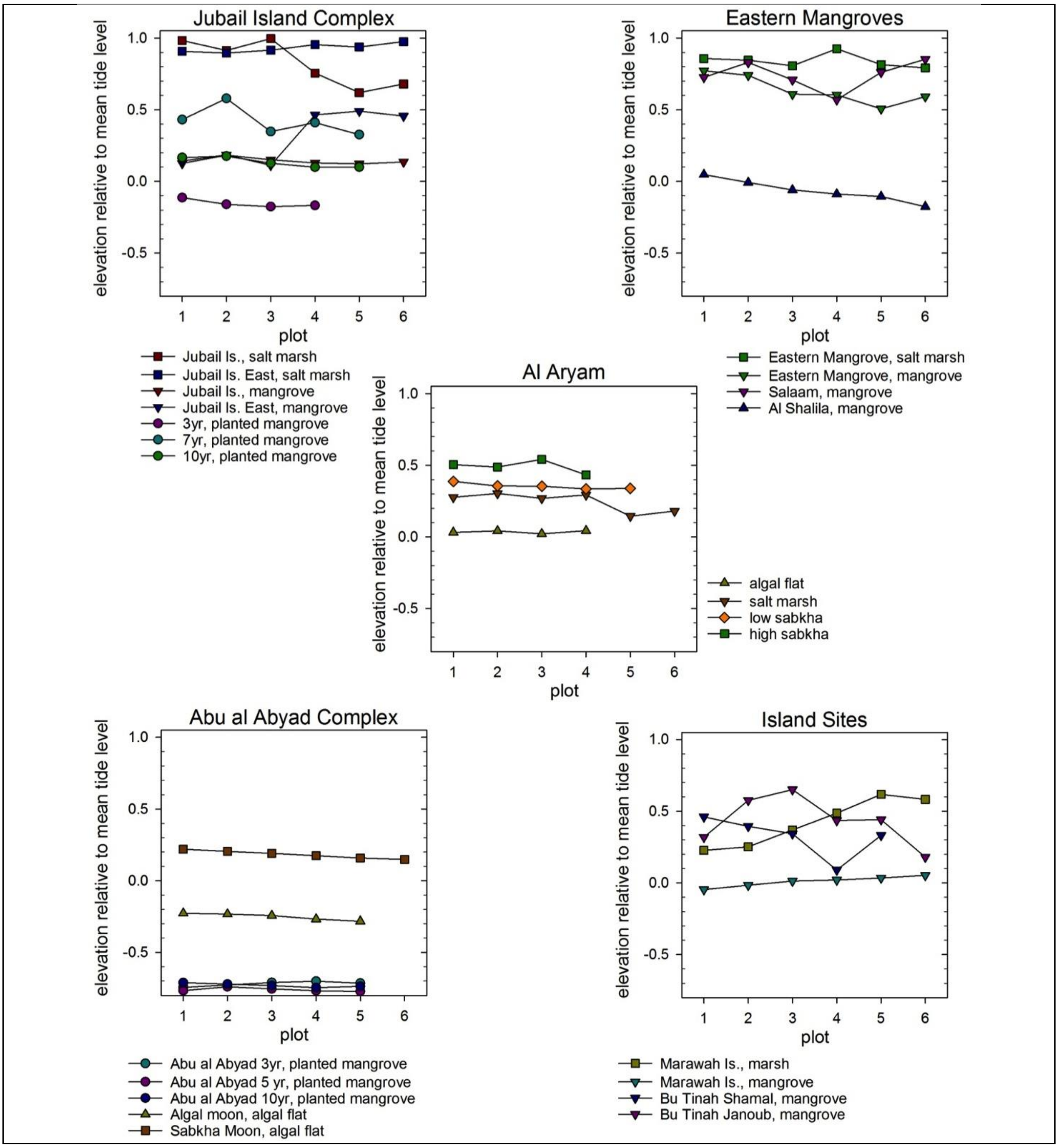


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 26

Surveyed plot elevations relative to m WGS84.

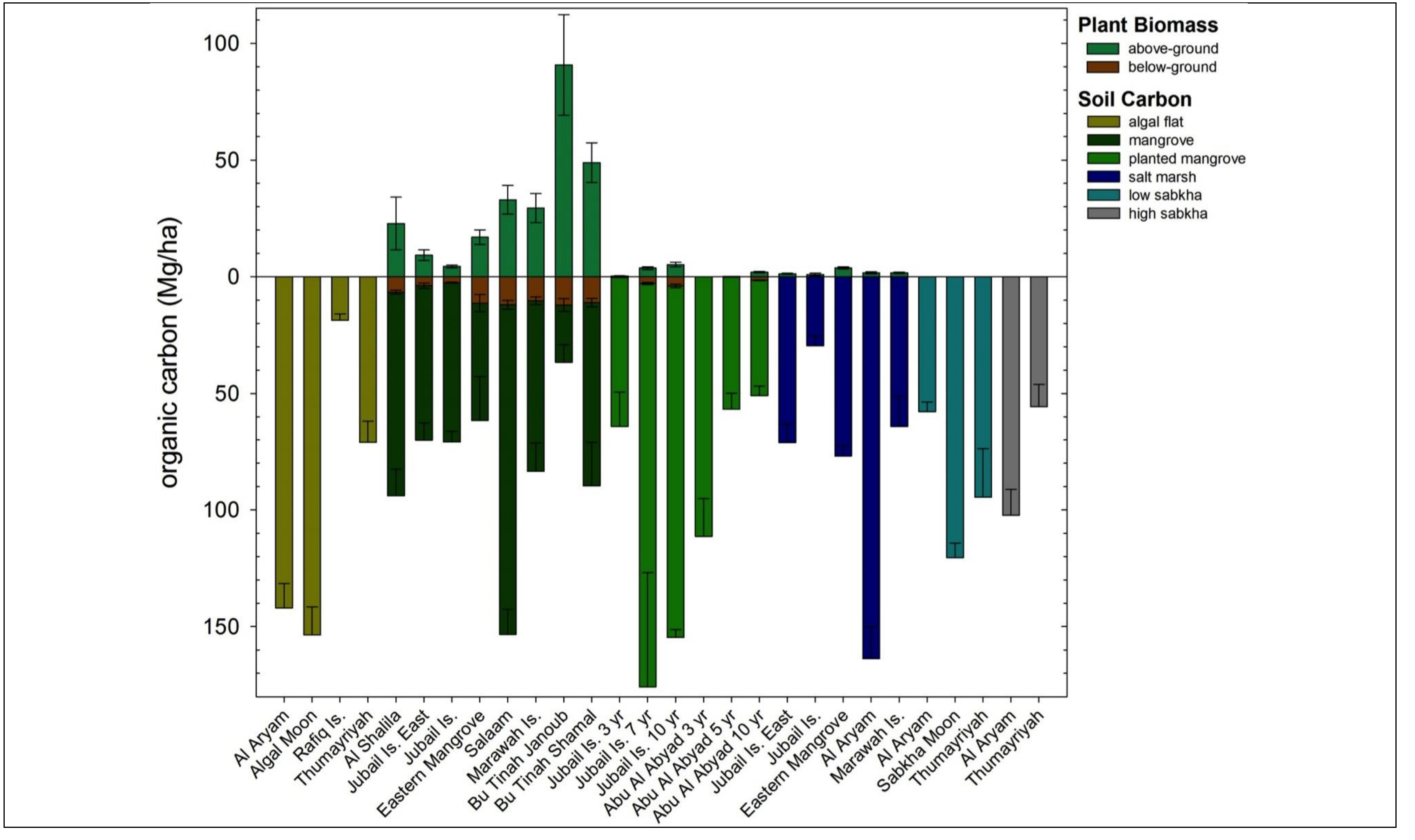


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 27

Plot elevations relative to mean tide level.

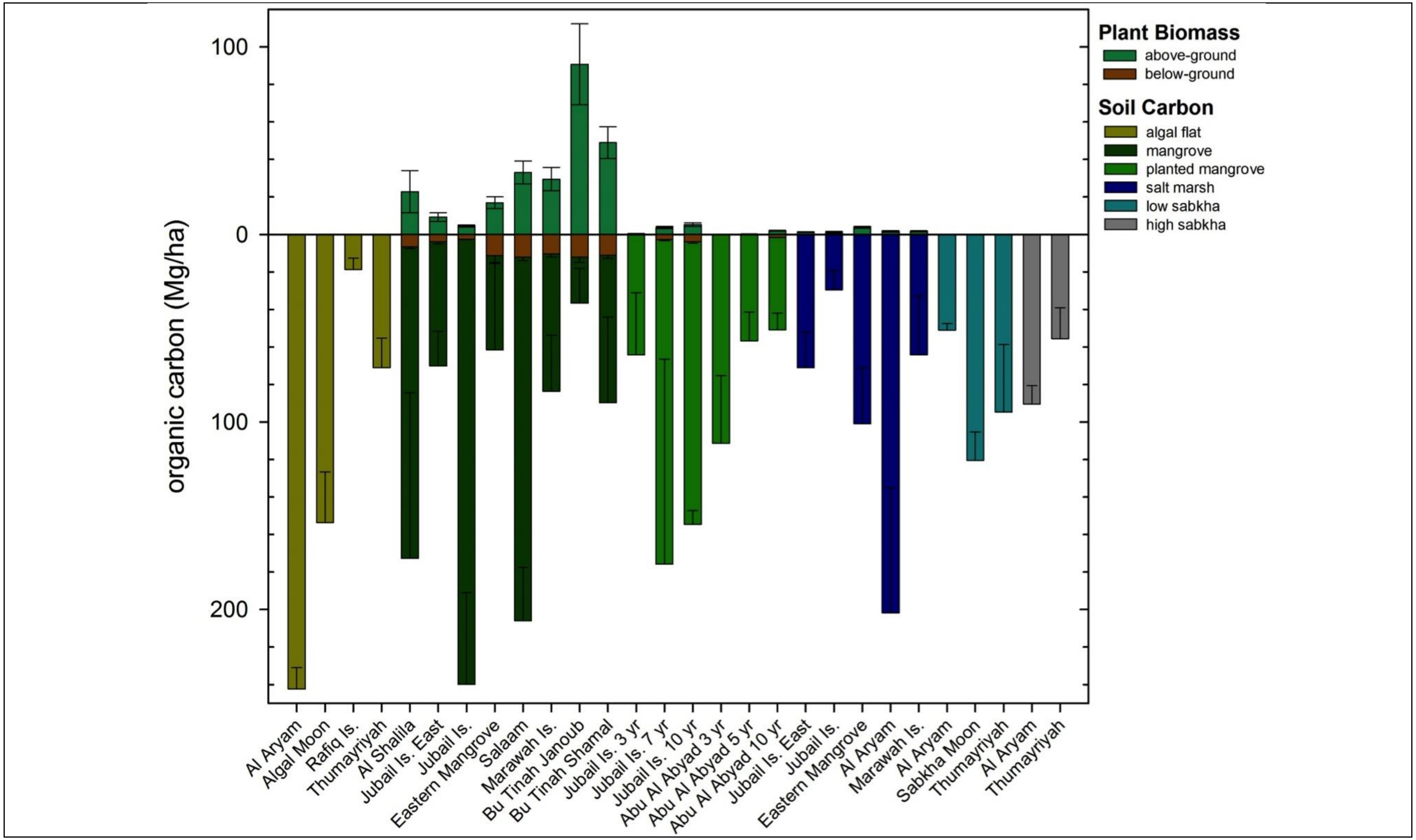


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 28

Carbon pools of intertidal ecosystems (soil carbon = top 1 m; no below-ground biomass for salt marshes; error bars = ±1 SE).

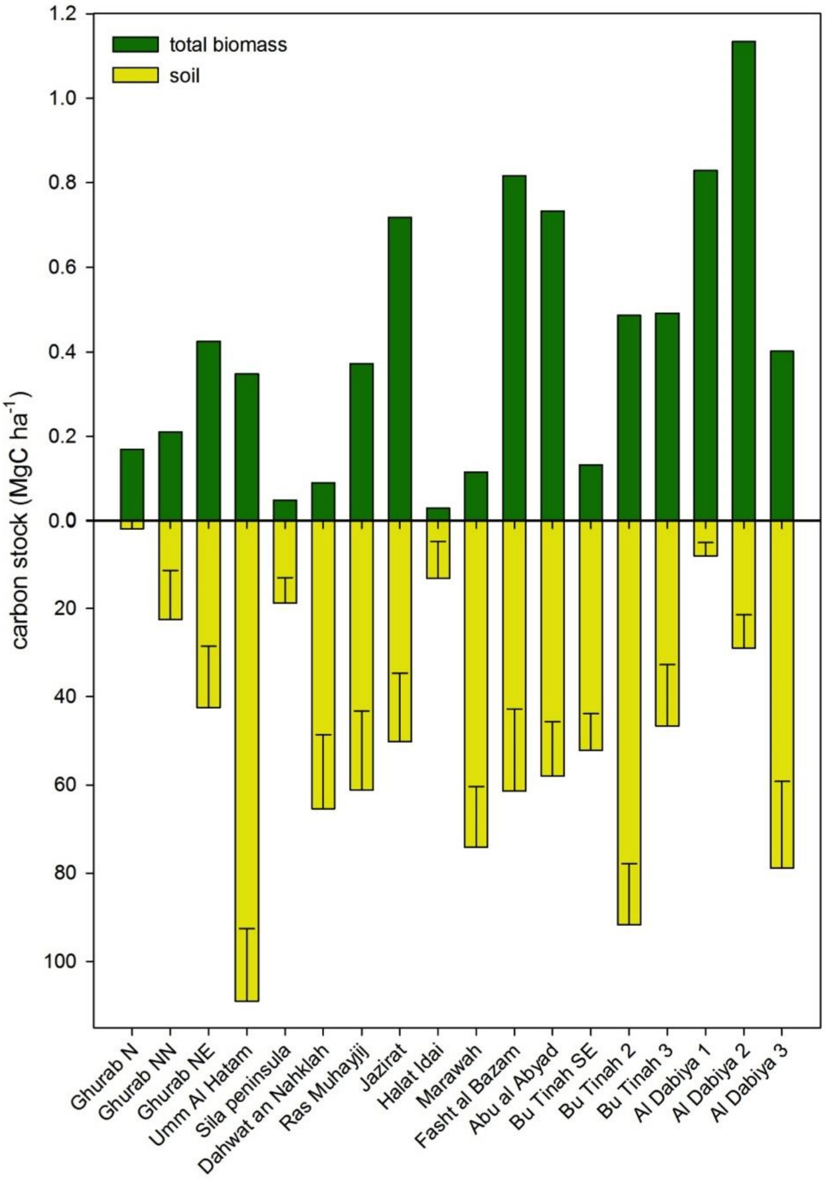


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 29

Total carbon pools of intertidal ecosystems (no below-ground biomass for salt marshes; error bars = ±1 SE).

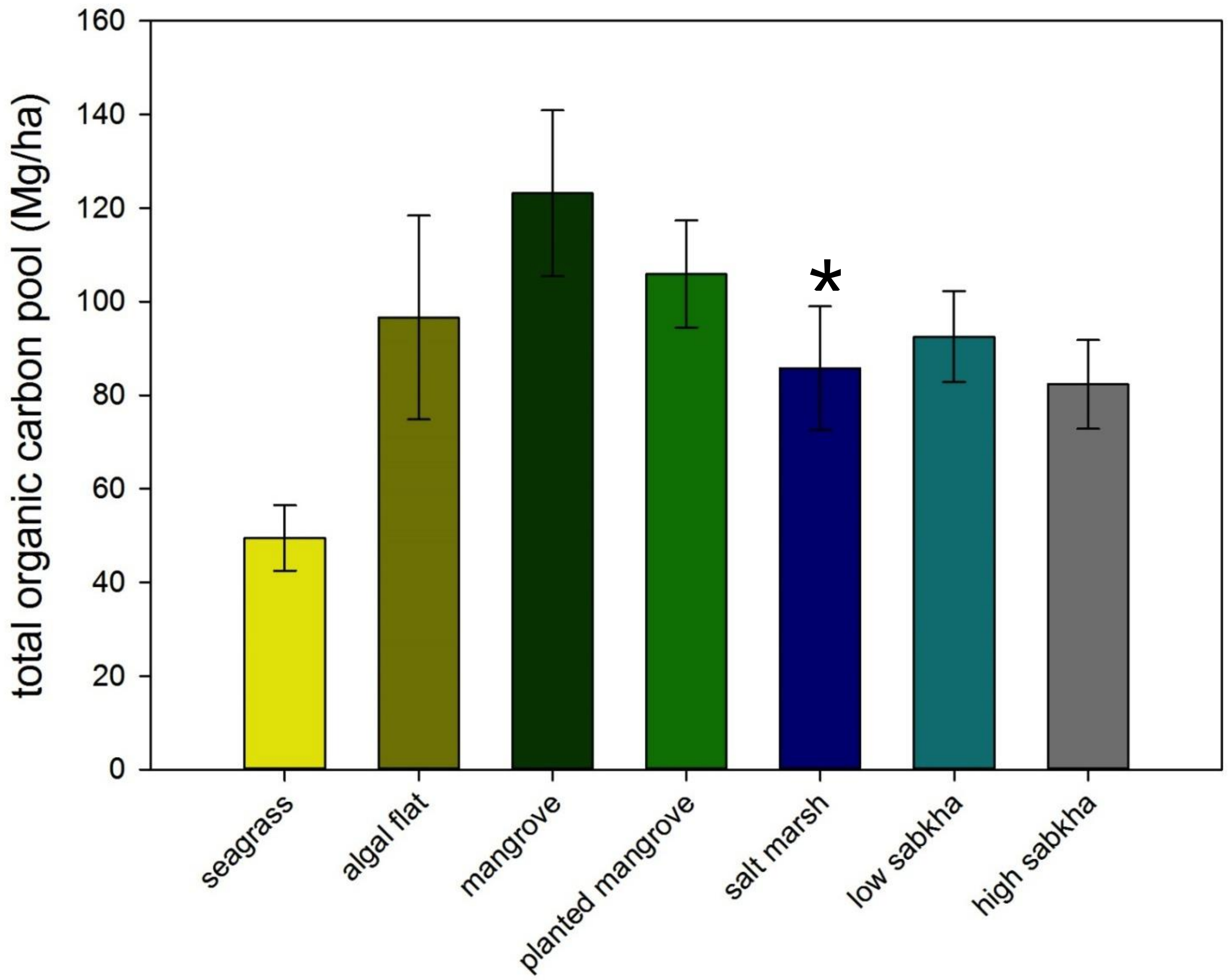


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 30

Carbon pools of all seagrass locations (error bars = ±1 Std).

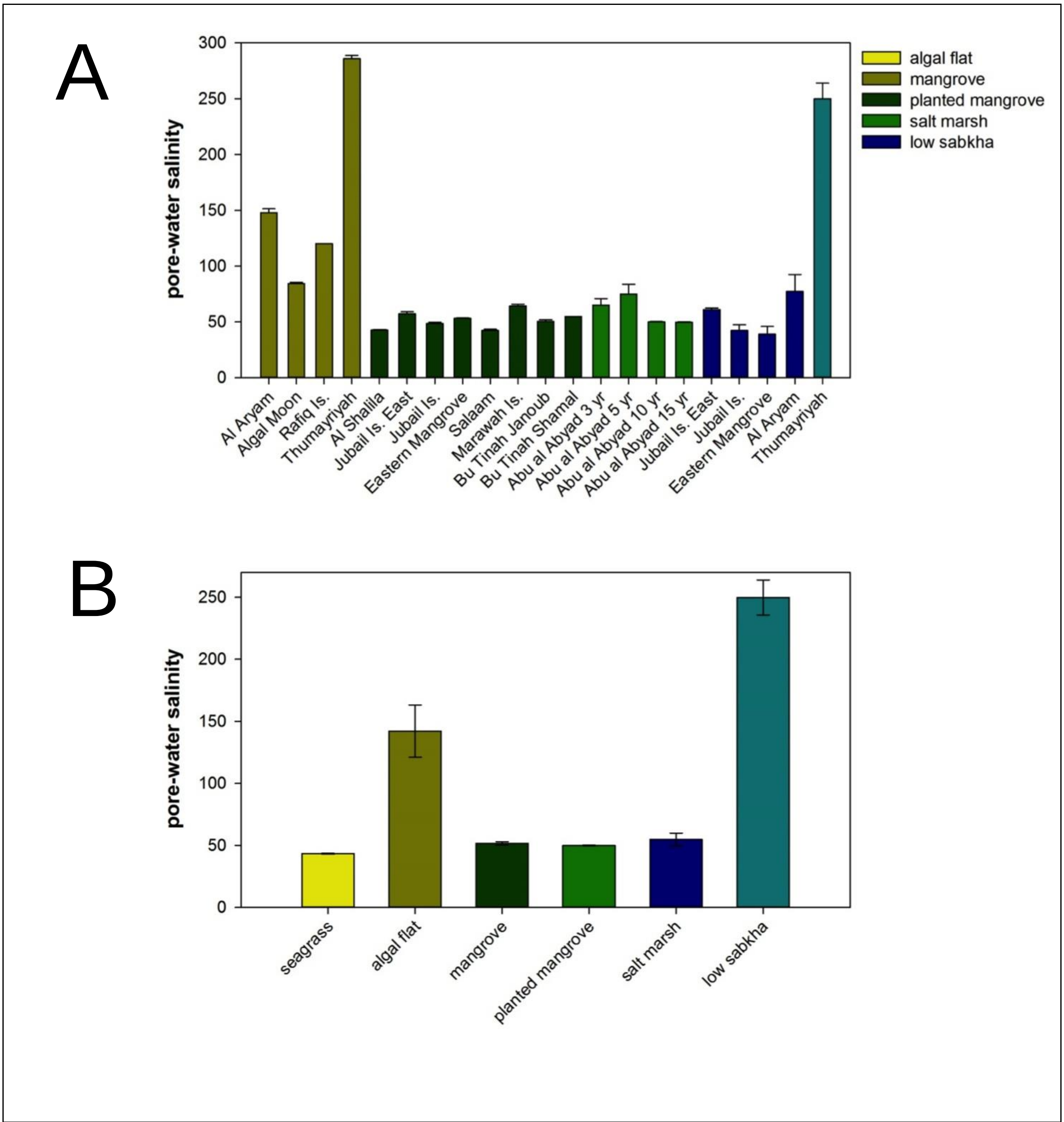


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 31

Average carbon pools (soil carbon in top 1m; * = no below-ground biomass; error bars = ±1SE).

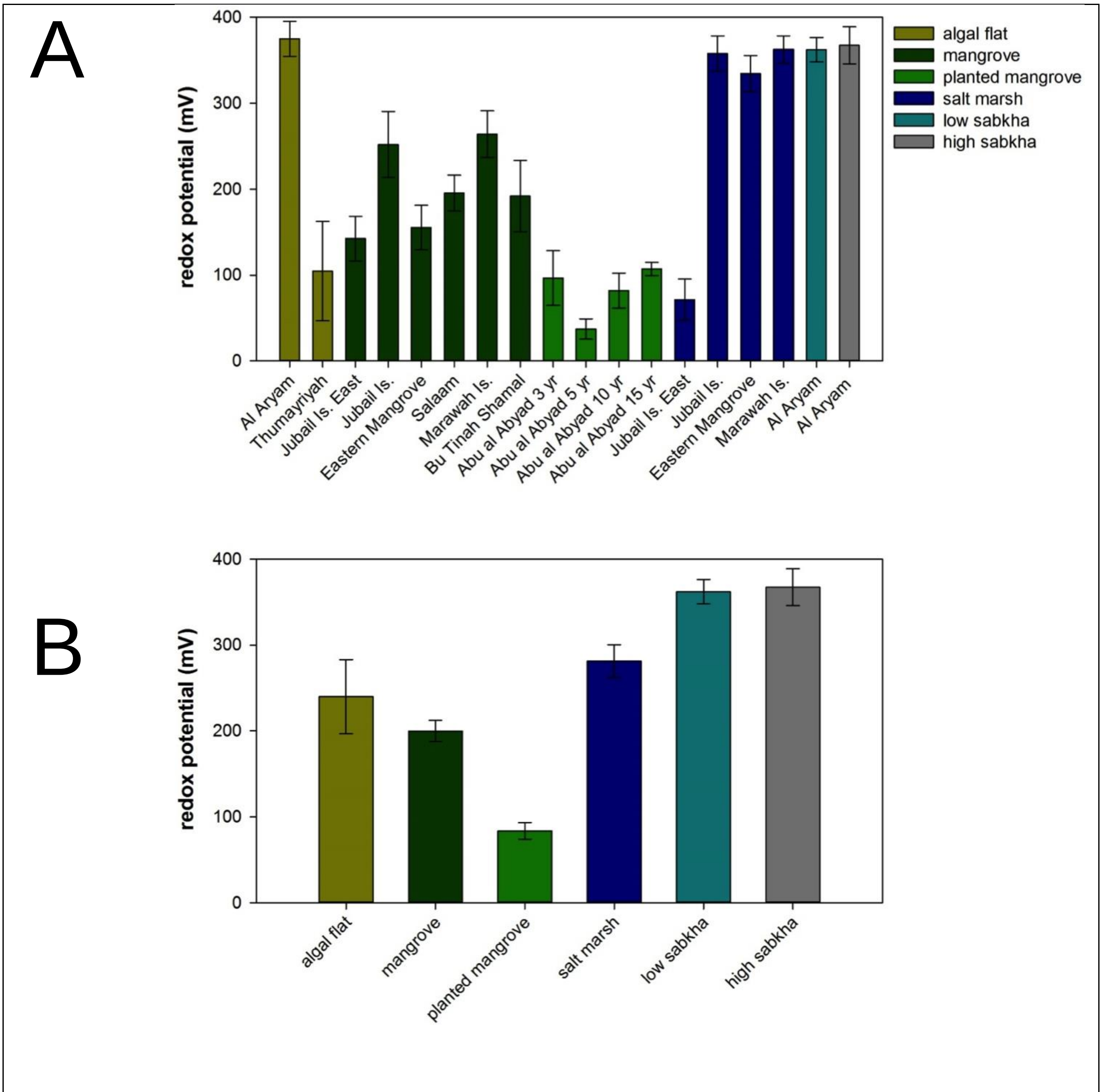


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 32

Pore-water salinity by a) site and b) ecosystem (seagrass salinity taken in water; error bars= ±1 SE).

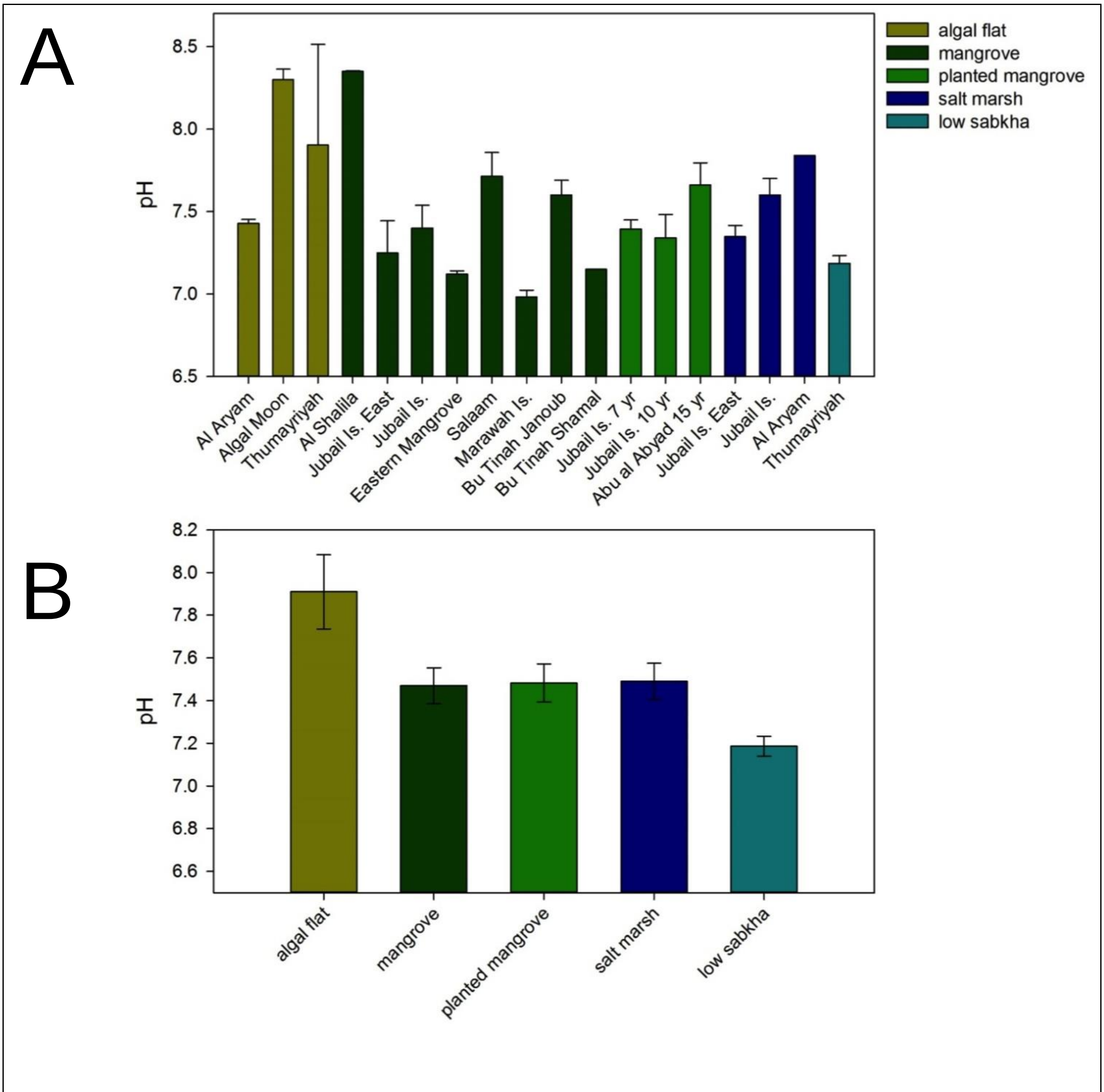


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 33

Average redox potential by a) site and b) ecosystem (error bars = ±1 SE).

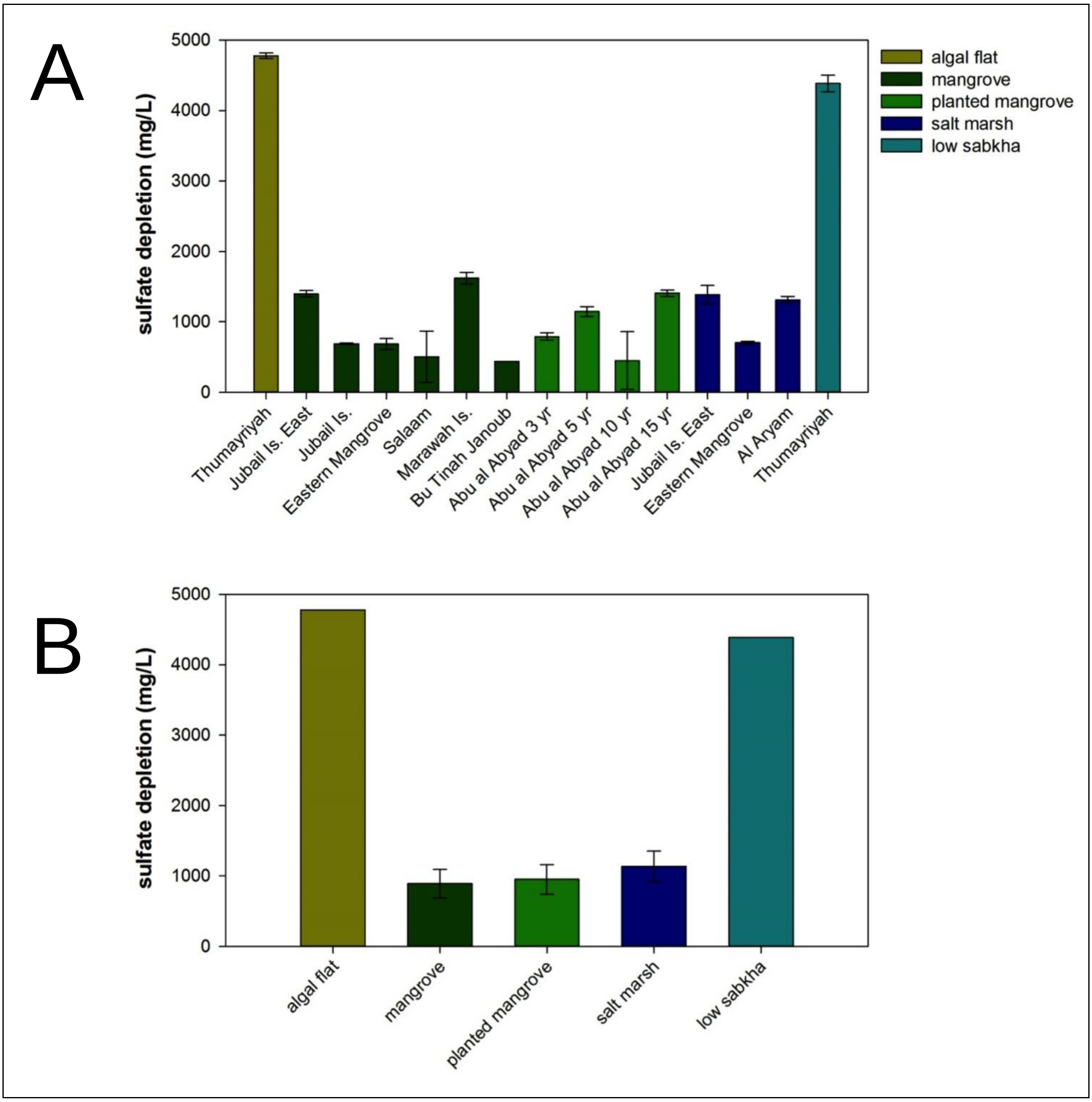


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 34

Average pH by a) site and b) ecosystem (error bars = ±1 SE).

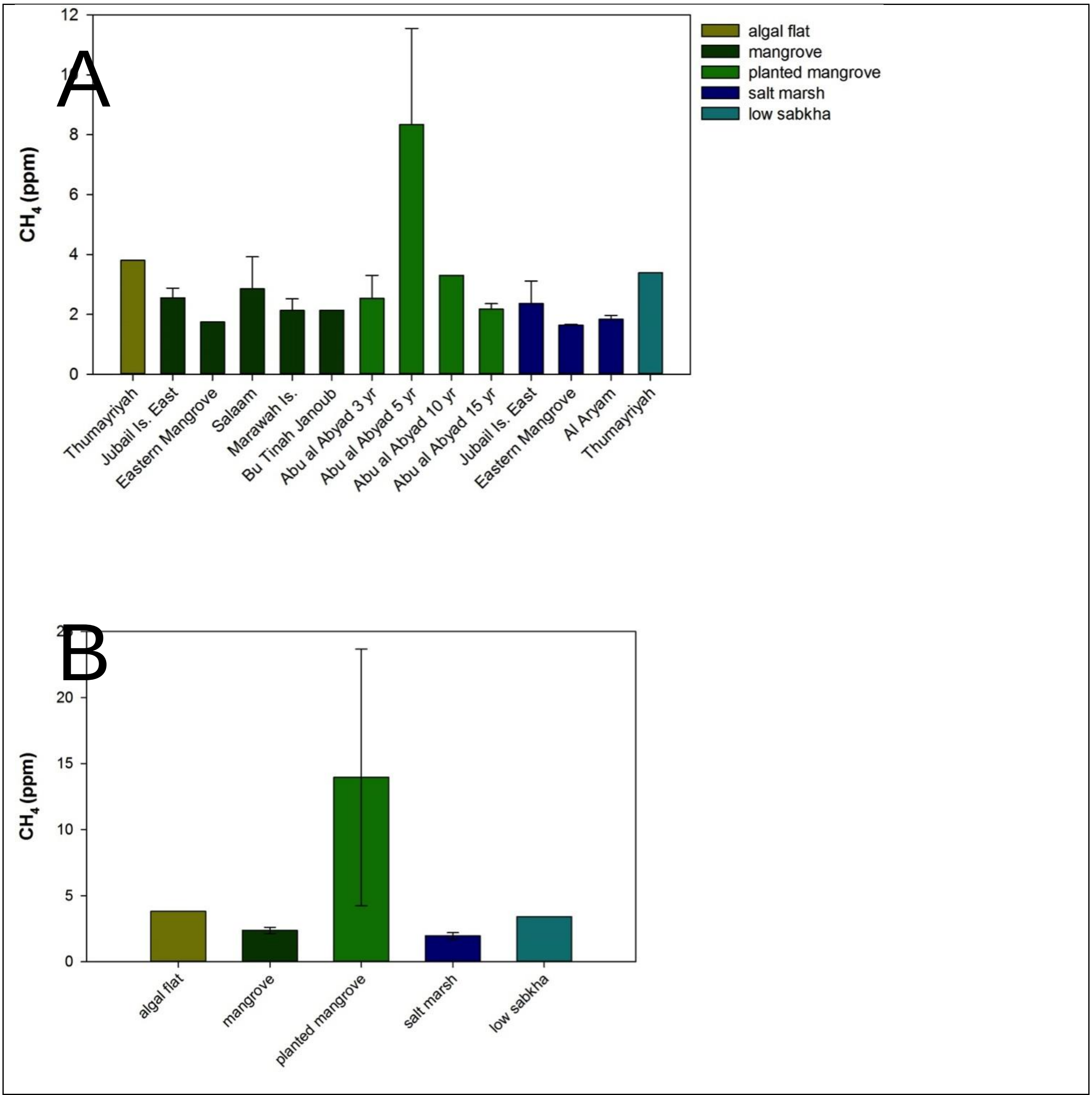


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 35

Pore-water sulphate depletion by a) site and b) ecosystem (error bars = ±1 SE).

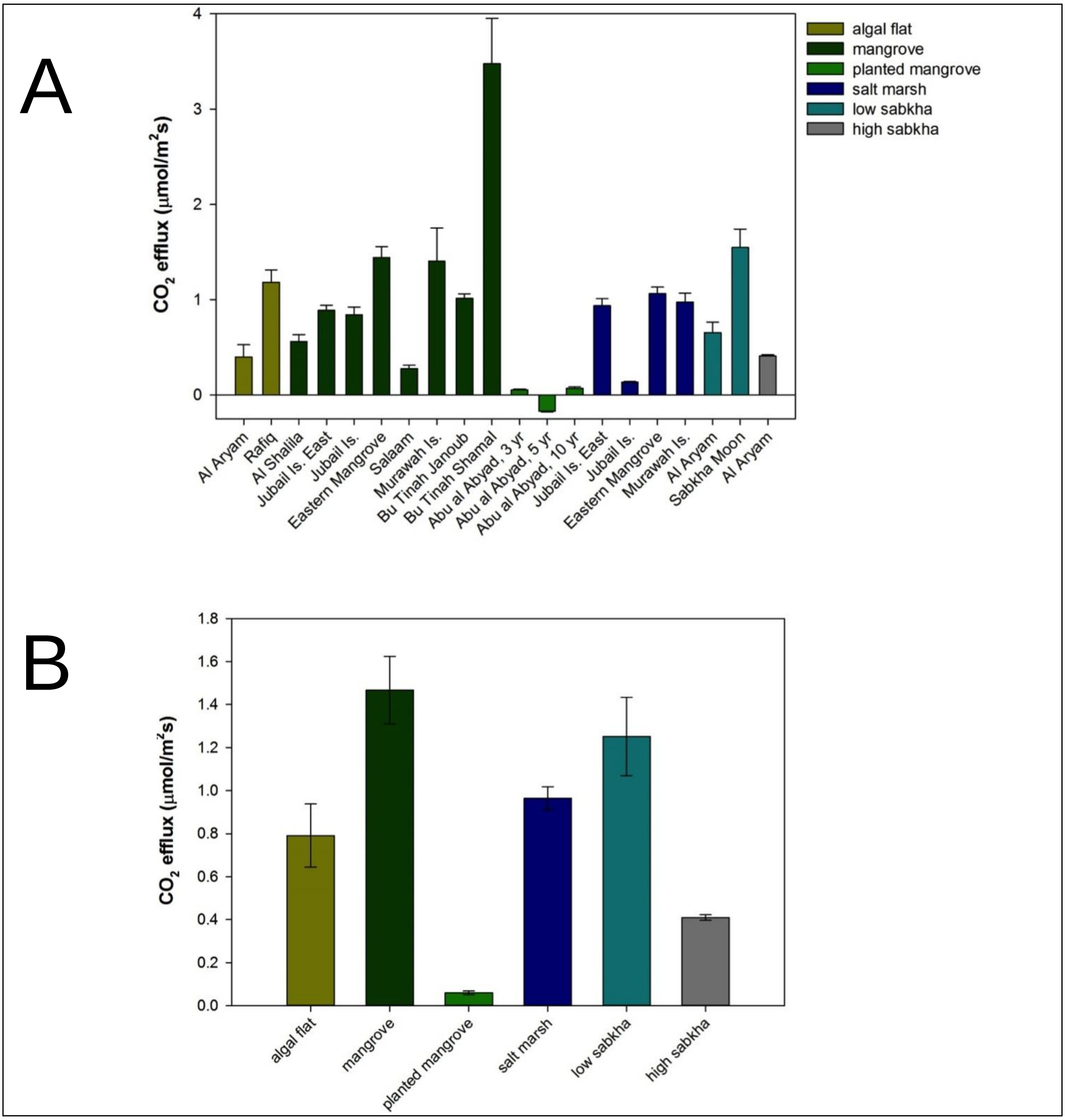


SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 36

Pore-water methane concentration by a) site and b) ecosystems (error bars = ±1 SE).



SOURCE: Abu Dhabi Blue Carbon Project

Abu Dhabi Blue Carbon Project

Figure 37

Average soil respiration values by a) site and b) ecosystem (error bars = ±1 SE).

6 Discussion of Results

6.1 Comparison of Abu Dhabi Blue Carbon Stocks

The accumulation of organic carbon in tidal wetland ecosystems represents the balance of carbon added through plant growth and deposition during floods, and carbon lost through decomposition or erosion. It is well known that these factors – plant production, microbial decomposition and sediment deposition – are strongly regulated by flooding frequency and salinity, which in turn are a function of elevation relative to tidal waters and rainfall/freshwater input. However, the literature on Blue Carbon is dominated by research on tidal wetlands in temperate and tropical ecosystems that are far wetter than the Arabian Peninsula. The research reported here represents a unique and exciting opportunity to broaden our understanding of how Blue Carbon ecosystems function in arid environments and identifies a new Blue Carbon ecosystem. As such, it is appropriate to begin by considering some of the basic features of Abu Dhabi wetlands and seagrasses that are relevant to formation of Blue Carbon pools.

As a global measure it is useful to assess the carbon stocks in biomass along with the top one meter soil as a means of comparison (Table 11). Though soil carbon stocks ranged from a low of 1.9 Mg ha^{-1} (shallow seagrass soils over bedrock) to a high of 164 Mg ha^{-1} (salt marsh) the means of soil carbon density across all ecosystems displayed a narrow range (80.4 – 102.3 Mg ha^{-1}). This reflected the potential of all intertidal ecosystems to hold layers of carbon amongst dominantly carbon poor sediments. Older natural stands of mangroves were found in places to possess an organic surface horizon (Figure 17a), either above less organic muds or low organic sands or bed rock material. Some algal flats were capped by a relatively deep (20-30 cm) organic surface above marine sands. Elsewhere through all ecosystems, relatively coarse, carbon deficient mineral sediment extended through the full depth of the surface meter, or commonly hid a buried organic horizon of former algal or mangrove soils (Figure 17bc). Deposits of seagrass beds, along with mangrove and algal flat soils that have been described in the literature (Kenig *et al.*, 1990) below sabkha deposits, were not encountered during this study.

Planted mangroves were found to have soil carbon contents that ranged from 51-155 Mg ha^{-1}, a comparable range to that of natural mangroves 37-154 Mg ha^{-1}**.** Higher carbon values of planted mangroves were in the Eastern Mangrove area and reflect the organic nature of the ambient soil material. Lower carbon values were found beneath plantations at Abu Al Abyad as a consequence of low carbon bearing substrate (graded sabkha), lower elevations, and insufficient time for significant carbon accumulation.

Natural mangroves held significantly more carbon in above-ground biomass (9.3 – 91 Mg ha^{-1}) than salt marshes (1 – 4 Mg ha^{-1}) and planted mangrove (0.02 – 5 Mg ha^{-1}). Considering total biomass carbon, which includes the roots as well as above ground living biomass carbon stocks in natural mangroves ranged from 7 to 122 Mg ha^{-1}, and for planted mangroves between 0.04 to 6.5 Mg ha^{-1}.

Significantly high values for carbon stocks within the natural mangroves over planted mangroves are indicative of the slow growing rate of *A. marina* in this environment.

The most basic feature of intertidal ecosystems to consider from a carbon perspective is elevation and its relationship to sea level. Based on relative differences in elevation at a single location, we determined that intertidal Blue Carbon ecosystems sort as follows (wet to dry): algal flats < created mangrove < mature mangrove < salt marsh < low sabkha < high sabkha. Mangrove and algal flats are dominantly found at mean tide elevation and above. At lower elevation productivity rapidly declines. This is demonstrated by comparing the two planted mangrove chronosequences (Figures 26 & 27, Table 9). Planted mangroves at Abu Al Abyad were planted at elevations approaching mean low tide and subject to submergence more than 75% of time. These mangroves were surviving, although had a large number of barnacles growing on the trunks, and by the age of ten years had accumulated 3.5 Mg ha^{-1}. By contrast on Jubail Island, mangroves were planted at elevations at or around mean tide elevation, and subject to flooding for 50% of time. Here, by the age of 10 years, carbon stocks of 9.2 Mg ha^{-1} had accumulated. Subtle differences in elevation relative to tidal waters can make a significant difference to the productivity of planted mangroves, as well as other intertidal plants. Differences in elevation are reflected in redox potential at 10 cm depth, which was generally lower at relatively low elevations (Figures 26, 27, & 33). Given the neutral to basic pore-water pH values (Figure 34), redox potentials suggest that these ecosystems do not have strongly reduced or anaerobic soils that favour carbon preservation. Nonetheless, the porewater chemistry indicates that anaerobic conditions do develop.

Methane pore-water concentrations greater than 2 ppm unambiguously indicate that anaerobic microbial respiration is occurring below the water table. Because the pore-water samples were taken from about 10 cm below the water table, the samples do not necessarily correspond to the same part of the soil profile where redox potential was measured. This is one of several possible reasons for the fact that methane concentration patterns across ecosystems do not strictly follow redox. A second indicator of carbon-preserving anaerobic conditions is the sulphate depletion ratio, which shows consumption of the sulphate anion by strictly anaerobic bacteria. All sites showed very high levels of sulphate consumption (Figure 35), with particularly high depletion at the hypersaline Thumayriyah site where sulphate is very abundant but also very depleted. Despite the abundance of sulphate at Thumayriyah, it is possible that high sulphate consumption there contributes to the relatively high pore-water methane concentrations, and that methane emissions from this site may be high compared to other Blue Carbon ecosystems in the Emirate. If so, this is an important observation as it means that the salinity-methane relationship runs counter to expectations from less arid ecosystems; specifically, that methane emissions decrease with increasing salinity.

The ability to draw inferences from the soil respiration data (Figure 37) is limited by the fact that the measurement is instantaneous and subject to rapid change depending on soil conditions at the moment it was sampled. Nevertheless, there was a non-significant, positive relationship between the total ecosystem carbon pool and CO_2 emissions across the intertidal ecosystems. The CO_2 emissions data demonstrate that there is active carbon cycling (i.e. plant and/or microbial respiration) in all of the ecosystems sampled, including algal flats and sabkha that lack vascular plants. Because microbial respiration requires a labile carbon source, it suggests that some potential exists for carbon loss from pools even in these non-traditional Blue Carbon systems.Two ecosystems were sampled that, prior to this study, were not considered to be Blue Carbon ecosystems: algal flats and coastal sabkha.

The data strongly support the inclusion of algal flats as a Blue Carbon ecosystem. Surface soils of algal mats had low DBD, which is indicative of the presence of organic matter, and soil organic carbon density greater than 0.02 g cm^{-3} (Figure 18f), which is comparable to many mature mangrove and salt marsh sites. Organic carbon predominantly was restricted to the soil surface down to 20cm (Figure 18f) though buried organic horizons at less than 1 meter depth were encountered; therefore, effort should be made to reduce disturbance of algal flat areas.

Due to its supratidal location and lack of active carbon sequestration, coastal sabkha is not considered to be an active Blue Carbon ecosystem; however, buried layers of mangrove paleosols and algal flats were encountered within the soil (Figure 17) and preserve carbon stores beneath the soil surface. Disturbance of coastal sabkha, specifically excavation, will unearth these buried carbon stores, expose them to the air, and release stocks.

6.2 Emissions of CO_2 with Destruction of Coastal Wetlands

The preservation of sequestered soil carbon stocks is maintained when soil conditions are wet and oxygen levels are low. Activities that drain wetland soils, such as excavation and placement in upland areas, would release much if not all of the carbon stored. Destruction of living biomass will also degrade readily, unless preserve as wood products, and carbon stocks can be assumed to have been released with wetland destruction.

Excavation of former Blue Carbon wetland soils buried beneath coastal sabkha soils, or dredging through mangrove or seagrass sediments and placement of material above water levels, will expose the carbon to aeration, likely resulting in stock release. There is potential that if placed and maintained in very arid conditions some carbon in buried dry soils is preserved. More detailed analysis to track the fate of carbon with relocation is required. The placement of fill on organic soils is akin to the advancement across historic coastal wetlands. Buried organic soils maintained wet would therefore hold soil carbon pools and, although this would mitigate potential release, carbon sequestration will be halted.

6.3 Comparison with Blue Carbon Stocks in Other Regions

6.3.1 Mangroves

Mangrove carbon stock can vary widely depending on latitude, salinity, tidal flushing, and nutrient availability and it is common to see stands of the same species having varying heights depending on their location (ie, tall and dwarf stands) (Donato *et al.* 2011; Adame et al 2013; Kauffman *et al.* in press). Comparing stocks measured in Abu Dhabi to those throughout the world, values are among the lowest (Figure 38). Above-ground storage is comparable to dwarf stands in the Dominican Republic although below-ground storage is the lowest documented across all stands examined (Figure 38). Despite the lower numbers, mangroves in Abu Dhabi are sequestering a significant amount of carbon, more-so than other local Blue Carbon ecosystems.

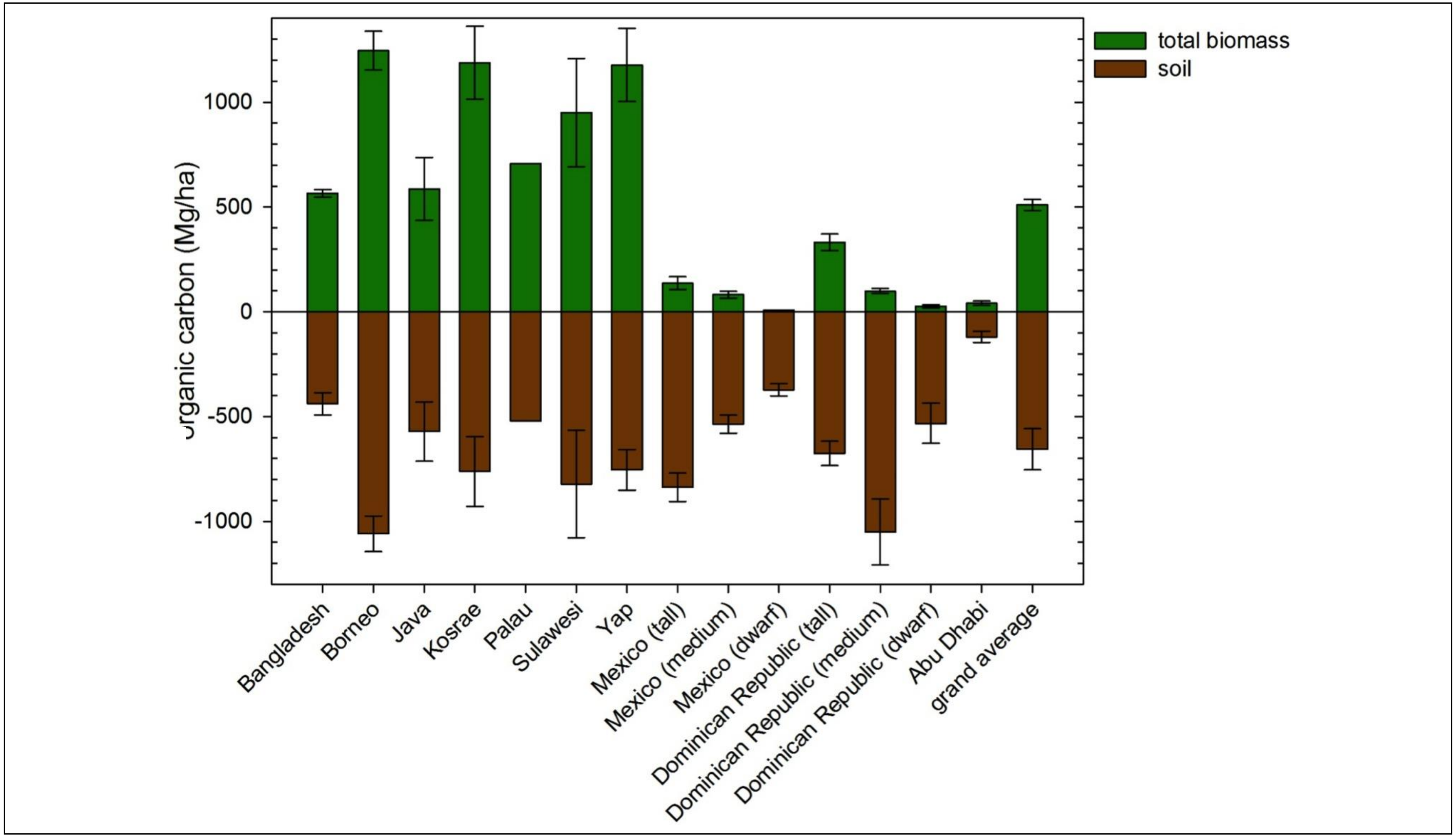
6.3.2 Salt Marshes

To date, the majority of carbon stock assessments in salt marshes have occurred in marshes dominated by the grass genus *Spartina*, and predominantly by the species *S. alterniflora* (Chmura *et al.* 2003), which confound direct comparisons with the Abu Dhabi shrub species that dominates marshes, *Arthrocnemum macrostachyum*. Above-ground carbon stocks of *A. macrostachyum* are considerably less than those measured in the SE and NE of the United States, which are dominated by *S. alterniflora* (Figure 39). Given the woody morphology of *A. macrostachyum*, a more apt comparison is with salt marshes found on the Pacific coast of the United States that are dominated by a woody species from the same family (Chenopodiaceae) as *A. macrostachyum*, namely *Salicornia pacifica*. The available data suggest that above-ground carbon stocks in *S. pacifica*-dominated marshes are twice to three times as large as Abu Dhabi marshes: 4.8-7.3 vs 1.9 MgC ha^{-1} (Schile *et al.* 2011). Soil carbon stocks measured to a depth of just 50cm in *S. pacifica* salt marshes of San Francisco Bay average 112 MgC ha^{-1} (Callaway *et al.* 2012 and unpublished data), which is more than the soil carbon stock of Abu Dhabi marshes measured up to 100cm deep. This difference in soil carbon stock is due to the influence of one or more factors: (i) plant production (especially root production), (ii) preservation of carbon, (iii) dilution by mineral sediment inputs, and (iv) the time period over which carbon has been accumulating. We do not have sufficient data to disentangle these factors, but note evidence that time since establishment contributes to relatively small soil carbon pool sizes in Abu Dhabi. Many soil profiles formed under the influence of salt marsh vegetation in the United States can be dated back to 6,000 years before present (Megonigal, per. comm). We do not have the data to evaluate the age of Abu Dhabi soil profiles, but buried algal layers and former mangrove soil surfaces suggest periods of rapid burial and loss of primary production. Thus, it is possible that seaward transgression in Abu Dhabi and the ephemeral nature of dune systems (Evans *et al.* 1989) prevents salt marsh plant carbon inputs from persisting in one location long enough to accumulate large soil carbon pools (Craft *et al.* 2003).

6.3.3 Seagrasses

As with mangroves, seagrass carbon storage varies globally due to a number of variables (salinity, water depth, species, disturbance, and nutrients, among others), with below-ground storage varying more than above-ground (Figure 40). Seagrass above-ground carbon storage in Abu Dhabi is comparable to sites in the Indopacific (Fourqurean *et al.* 2012); however, below-ground storage is among the lowest out of locations studied (Figure 40). The seagrass beds of Abu Dhabi have relatively low living biomass compared to seagrass beds from other areas of the world, largely because of the small stature and short life spans of the individual seagrass plants typical of the species found in the Arabian Gulf. The worldwide average C stock in living seagrass meadows ranges from 0.001 to 23.382 MgC ha^{-1}, with a mean of 2.51 +/- 0.49 MgC ha^{-1} (Fourqurean *et al.* 2012). In contrast, the maximum C stock of living seagrass was 1.13 MgC ha^{-1} at our Al Dabiya 2 site, and the mean was only 0.4 +/- 0.1 MgC ha^{-1}, or not even 1/6 the average reported seagrass biomass worldwide. However, the expansive distribution of seagrasses along the coast of Abu Dhabi supports a considerable stock of seagrass biomass carbon, albeit at relatively low density.

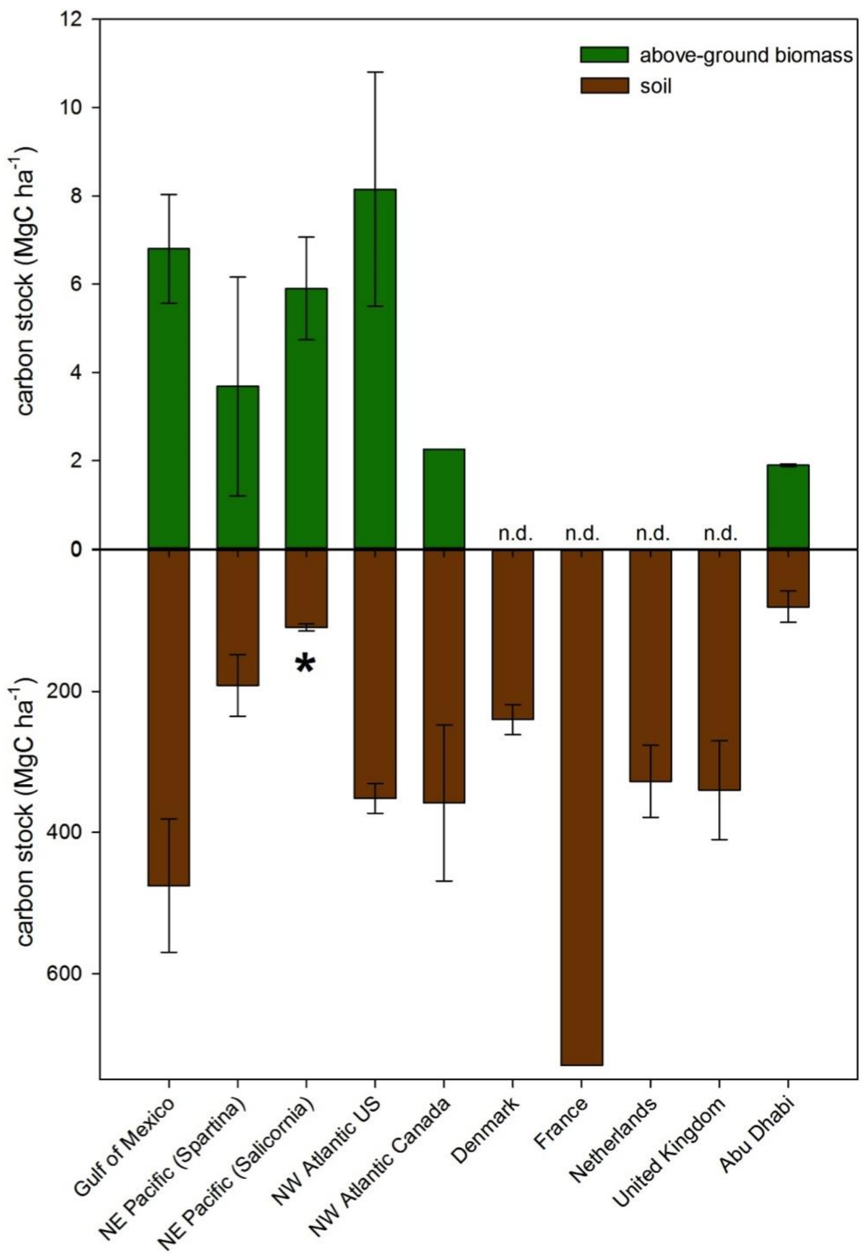
Compared to values of C_{org} from seagrass beds around the world, Abu Dhabi seagrass soils had relatively low C_{org} (Figure 15b). The global average C_{org} from seagrass beds has been reported to range between 0 and 48.2%, with a mean of 2.0% +/- 0.1% (Fourqurean *et al.* 2012). The average C_{org} measured in Abu Dhabi seagrasses was 0.64 ± 0.39 %, comparable to the C_{org} observed in temperate seagrass meadows in silicious mineral environments dominated by the seagrass Zostera marina. The low C_{org} of the Abu Dhabi seagrass soils was reflected in the relatively high DBD values observed. The average Abu Dhabi DBD was 1.37 ± 0.04 g cm^{-3}, compared to a global average of 1.03 +/- 0.02 g cm^{-3} (Fourqurean et al 2012). The low C_{org} and high DBD are typical of mineral-based soil deposits. As a function of high mineral content and low C_{org}, soil C stores on an aerial basis in Abu Dhabi seagrasses were generally below the world median value of 139.7 MgC ha^{-1} (Figure 21b).



SOURCE: Abu Dhabi Blue Carbon Project; Donato et al. 2011; Adame et al. 2013; Kauffman et al. in press

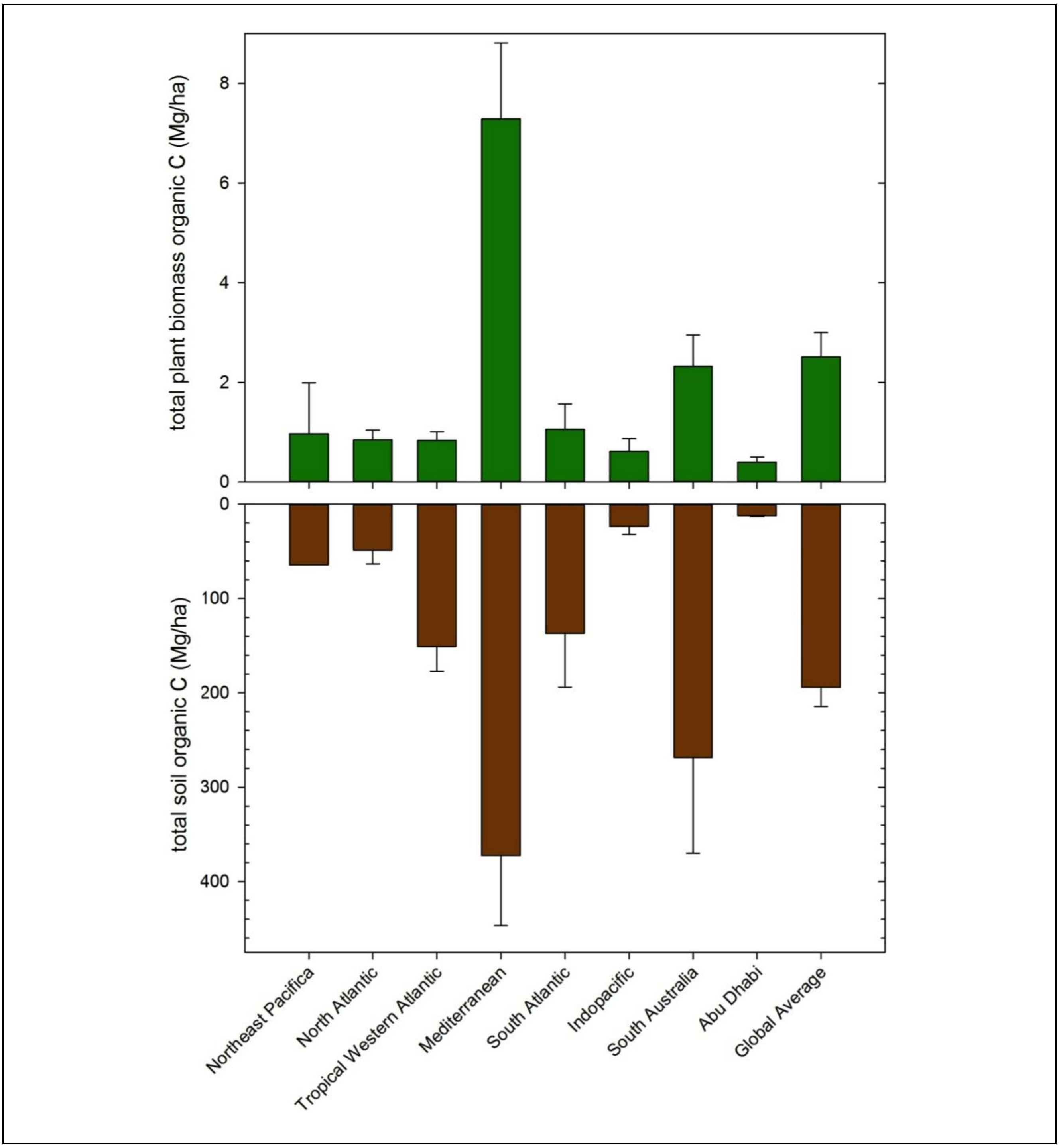
Figure 38

Global comparison of mangrove plant and soil organic carbon pools (error bars =±1 SE).



SOURCE: Abu Dhabi Blue Carbon Project; Chmura et al. 2003; Callaway et al. 2012; Schile et al. 2011

Abu Dhabi Blue Carbon Project
Figure 39
Global comparison of salt marsh plant and soil organic carbon pools (* = top 50cm of soil; error bars =±1 SE).



SOURCE: Abu Dhabi Blue Carbon Project; Fourqurean et al. 2012

Abu Dhabi Blue Carbon Project

Figure 40

Global comparison of seagrass plant and soil organic carbon pools (error bars =±1 SE).

7 Conclusions

7.1 Implications for other project Components

1. Carbon stocks of the coastal zones of Abu Dhabi are likely the highest stocks in the Emirate.
2. Abu Dhabi coastal ecosystems provide a variety of ecosystem services; climate change mitigation may be a subordinate service relative other functions such as supporting fish populations, biodiversity and cultural values.
3. Algal flats have been identified as a potentially new Blue Carbon ecosystem, one specific to arid, high salinity environments. Sabkhas have been identified as associated Blue Carbon ecosystems.
4. Carbon stock levels are small compared with many regions of the world, a reflection of the arid climate and temperature range.
5. Carbon stocks within Abu Dhabi Blue Carbon ecosystems fall below the range of those typically of interest to carbon finance framework, though are appropriate for inclusion into conservation and management activities.
6. Care should be taken when comparing the carbon stocks of natural and planted mangroves. While it was found within this study that the total carbon stock (soils plus biomass) of natural and planted mangroves were of similar magnitude, this belies the differences in biomass stocks and includes the soil components that existed prior to mangrove planting.

7.2 Key Messages

1. The Blue Carbon ecosystems of Abu Dhabi include intertidal habitats of mangroves, salt marshes, algal flats and subtidal seagrass meadows, likely hold more organic carbon per unit area than upland or terrestrial ecosystems.

2. Algal flats, an ecosystem specific to arid saline environments, are recognized as a new form of Blue Carbon ecosystems in this report. Algal flats, like other Blue Carbon ecosystems, sequester CO_2 from the atmosphere, and because of environmental conditions accumulate carbon within sediments.

3. Carbon stocks are held within two pools: soil and above-ground + root biomass. Only mangroves have significant quantities of carbon in above-ground and root biomass.

4. Soil carbon stocks are not readily predictable from surface observations due to the presence of buried historic organic layers. Comparing the top one meter of soil across all sampled ecosystems mean carbon stocks ranged from 80 to 102 MgC ha^{-1}. Higher values were found beneath older natural mangroves and algal flats that had built up organic surface soils. Individual high values were identified beneath other ecosystems at sites were buried soils where encountered. Otherwise, carbon stocks within soils were low.

5. Occupying the terrestrial environment, and not a site of active carbon sequestration, coastal sabkha is not recognized as a Blue Carbon ecosystem. However, there is evidence that in places coastal sabkha do cap buried former Blue Carbon soil deposits.

6. Conserving natural mangroves is a more effective means to protect carbon stocks that restoring mangrove.

7. Carbon stocks in natural mangrove stands was significantly higher than that of young plantations. Natural mangroves held in biomass between 9-91 MgC ha^{-1}, with a mean value of 32 MgC ha^{-1}. Ten years after planting, afforested mangrove held between 3.5 and 9.2 MgC ha^{-1} within tree biomass, and demonstrated negligible increases in soil carbon.

8. In the first years of restoration C sequestration is primarily in plant biomass. The inherent site variability and our sampling approaches were not sensitive enough to detect soil C sequestration. By the age of seven, up to 7.8 MgC ha^{-1} have been sequestered in plant mass and an unknown quantity in the soils. In the young plantations that we sampled we could not detect organic soils such as was observed in natural mangroves. But this would likely change with time. The effectiveness of carbon storage depends upon the health or productivity of the mangrove, which in turn depends upon the environmental conditions at which the sapling is planted.

9. The established approach of planting sampling rather than sediment likely significantly improves the success of mangrove afforestation actions. Those planted at or above mean tide elevation, but within intertidal elevations, grew faster than those planted below mean tide elevation.

10. Salt marshes and flooded intertidal areas of coastal sabkha hold similar quantities of carbon, 81 MgC/ ha and 75 MgC/ha, respectively, indicating that marsh productivity is quite low, little of the carbon produced by marshes is being stored, or both. Reduction-oxidation data indicate a high level of aeration within the marsh soils, conditions under which carbon is readily oxidized

11. Sea grass meadows have total ecosystem carbon stocks of 49 Mg ha^{-1}.

12. Across the landscape, based upon available survey maps, seagrass meadows hold the greatest quantity of carbon compared to other ecosystems; 7.9 x 10^6 Mg for mangroves 1.3 x 10^6 Mg for planted mangroves, 0.5 x 10^6 Mg for algal flats, and salt marsh at 0.4 x 10^6 Mg. The extent of intertidal coastal sabkha is unknown. The total area, and hence the total carbon stock of seagrass meadows is unknown. Currently seagrass is mapped to 3m below sea level but diver observations found seagrass to be widespread to depths of 14m or more.

13. Based upon comparisons of similar plant communities across the globe, the total stocks of carbon are low. Mangroves sampled in the wet tropics record total carbon stock values of between 400 Mg/ha to over 2000 Mg / ha, values 4-20 times greater than sampled in Abu Dhabi. Mangroves of the UAE are at the hyperarid and hypersaline extremes; these differences are likely a consequence of climate and salinity.

14. Stores of historic Blue Carbon, derived from buried seagrass, algal flat and mangrove soils are held beneath the coastal sabkha (Kenig *et al.*, 1990). Excavation of these soils and placement in dry conditions could results in a release of carbon dioxide to the atmosphere. The distribution and magnitude of these buried carbon stores is unknown.

15. Excavation of coastal sabkha and algal flats for the purpose of mangrove planting may not result in net greenhouse gas benefits. Planting of mangroves in suitable conditions without significant geomorphic disruption most likely will result in landscape net GHG reductions benefits, though GHG budget for project activities should be accounted for.

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Appendix A: Example forms

Plot Meta Data

Project:

Forest Type:________________________________ Name of area sampled: ______________________

Date: _________ Direction of central transect ________ Transect Length ___________________________

Crew Members:____ _____

Plot Location/Directions GPS Coordinates: Plot 1 Plot 2 Plot 3 Plot 4 Plot 5 Plot 6 Topography: Landscape position: Disturbance: Additional Notes:

Overstory Vegetation

PROJECT NAME:

SITE_______________FOREST TYPE_________________ Plot size (7 Meter radius if dbh is >5cm; 2 m if dbh is <5cm

or note differently here)___________

Date:______________ **Data /Recorder**_______________________________________

PLOT	DBH	Crown diameter	L/D	Status / class		PLOT	DBH	Crown diameter	L/D	Status / class

Data Entry: Name__________________Date_______Checked by__________Date____________

Understory Vegetation/Litter

(Not normally used in mangrove)

Project:

Fresh weight of vegetation in two combined microplots/subplot

Site____________________

Dimensions of microplot___________________________________

Date:__________________Data Collection/Recorder_________________________________

Plot	Subplot	Fresh weight (g)	Wet weight subsample	Dry weight subsample	Notes

Wood Debris

Project:_________________ SITE___________________________

Date:______________Data collection________________Data Recording ____________________

Four, 14m transects at 45° to subplot center axis. Medium=2.5-7.6cm (9m-14m) Large ≥ 7.5cm (2m-14m count and measure).

PLOT	TRANSECT	>7.5cm sound					>7.5 rotten					2.5-7.5					

Data Entry: Name___________________Date_______Checked by___________Date____________

Soil samples for Carbon and bulk density

PROJECT: SITE Name _____________

Vegetation type _________________Type of sampler used____________

Date:______________ Data Collection/Recorder_____________Size of samples collected_______

Plot number	Soil Depth	Can Number		Plot number	Soil Depth	Can Number