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Carbon Storage in Seagrass Beds of Abu Dhabi, United Arab Emirates

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Abstract "Blue Carbon" initiatives have highlighted the significant role of seagrasses in organic carbon (C_{org}) burial and sequestration. However, global databases on the extent of C_{org} stocks in seagrass ecosystems are largely comprised of studies conducted in monospecific beds from a limited number of regions, thus potentially biasing global estimates. To better characterize carbon stocks in seagrass beds of varying structure and composition, and to further expand the current "Blue Carbon" database to under-represented regions, we evaluate the extent of C_{org} stocks in the relatively undocumented seagrass meadows of the Arabian Gulf. Surveys were conducted along the coast of Abu Dhabi (UAE) and encompassed sites ranging from sheltered embayments to offshore islands. Seagrass beds consisted of *Halodule uninervis*, *Halophila ovalis* and *Halophila stipulacea*. While seagrasses were widely distributed along the coast, both living and soil C_{org} stores were relatively modest on an areal basis. Total seagrass biomass ranged from 0.03 to 1.13 Mg C ha^{-1}, with a mean of 0.4±0.1 (±SEM), and soil C_{org} stocks (as estimated over the top meter) ranged from 1.9 to 109 Mg C ha^{-1}, with a mean of 49.1±7.0 (±SEM). However, owing to the expansive distribution of seagrasses in the Arabian Gulf, seagrass "Blue Carbon" stocks were large, with 400 Gg C stored in living seagrass biomass and 49.1 Tg C stored in soils. Thus, despite low C_{org} stores for any given location, the overall contribution of seagrass beds to carbon storage are relatively large given their extensive coverage. This research adds to a growing global dataset on carbon stocks and further demonstrates that even seagrass beds dominated by small-bodied species function to store carbon in coastal environments.

Keywords Blue carbon · Carbon sequestration · Organic carbon · Soil C_{org} · *Halophila stipulacea* · *Halophila ovalis* · *Halodule uninervis*

Introduction

Seagrass meadows are hotspots for carbon accumulation in the biosphere, with stores comparable to temperate and tropical forests (Fourqurean et al. 2012a). Given their ability to capture and retain carbon, seagrass beds (along with other coastal ecosystems such as mangrove forests and tidal marshes) play a significant role in global carbon cycling and therefore could prove to be important components of global climate change (Duarte et al. 2005; McLeod et al. 2011; Smith 1981). Anthropogenic greenhouse gas emissions have contributed vast quantities of CO_2 to the atmospheric reservoir, of which considerable amounts can be absorbed and buried by vegetated marine systems, at rates of nearly 111.4 Tg C year^{-1} (Duarte et al. 2005). Through land-use conversion and the consequences of human alteration of water quality in coastal areas, the conversion of stored carbon from coastal ecosystems (called "Blue Carbon") to atmospheric CO_2 currently represents a substantial economic burden, ranging in annual damages of up to US$ 42 billion (Pendleton et al. 2012).

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Globally, seagrass meadows represent one of the largest marine sinks for organic carbon (Duarte et al. 2005; Fourqurean et al. 2012a; Smith 1981). While occupying less than 1 % of the world's oceans on an areal basis, seagrass ecosystems have been estimated to bury 27.4 Tg C year^{-1}, accounting for nearly 10 % of oceanic carbon burial (Duarte et al. 2005). In addition to the burial of organic carbon (C_{org}) produced within the seagrass beds, seagrasses facilitate the deposition of imported, allochthonous C_{org} via particle trapping from the water column and sediment stabilization (Agawin and Duarte 2002; Gacia and Duarte 2001; Hendriks et al. 2008; Kennedy et al. 2010). Moreover, the oxygen-poor anaerobic soils of seagrass meadows prevent C_{org} remineralization and tend to promote long-term sequestration (Mateo et al. 1997; Pedersen et al. 2011). As such, conservative estimates of carbon storage in the soils of seagrass beds worldwide range from 4.2 to 8.4 Pg carbon (Fourqurean et al. 2012a). While these estimates aid in placing overall boundaries on the relative magnitude of carbon storage, considerable variation exists in both living and soil C_{org} stores for any given location. Based upon a global dataset, Fourqurean et al. (2012a) report a range in seagrass biomass of over 5 orders of magnitude (0.001–23.382 Mg C_{org} ha^{-1}) and a range in soil $\mathrm{C_{org}}$ from 0.002 to 48.238 (percent dry weight). Such variation is likely attributable to the influence of multiple biological and environmental factors that can largely alter rates of C_{org} deposition (Lavery et al. 2013). Moreover, reliable data on stocks of soil C_{org} are limited to sites within the Mediterranean, Northern Atlantic, and eastern Indian Oceans. Thus, global estimates may be heavily influenced by values from these geographic regions (Fourqurean et al. 2012a). In order to improve global estimates of C_{org} storage in seagrass meadows, research is needed that expands the current database to alternate, poorly documented locations with varying geomorphological and biological characteristics.

Seagrasses display considerable variation in morphological and structural attributes that can alter rates of organic matter production and accumulation, particularly when integrated across large spatial and temporal scales (Mateo et al. 2006). In addition to varying rates of primary production, species-specific distinctions in (1) above/belowground biomass, (2) degree of refractory material, and (3) canopy structure and morphology can all serve to influence rates of soil C_{org} sequestration in seagrass meadows (Lavery et al. 2013). For example, some of the highest estimates of C_{org} originate from locations in the Mediterranean (Serrano et al. 2012), dominated by the relatively large-bodied species, *Posidonia oceanica*, which produces substantial quantities of refractory belowground biomass (Romero et al. 1994) and a structurally complex canopy, aiding in particle trapping and sediment stabilization (Gacia and Duarte 2001; Mateo et al. 1997; Pedersen et al. 2011). In addition to variation in C_{org} storage driven by species differences, there exist broader environmental factors that can further influence rates of sediment accumulation, such as site depth, flow regimes, and exposure to storm activity (Hedges and Keil 1995; Manca et al. 2012; van Katwijk et al. 2010).

In order to geographically expand upon a limited dataset, this study examines the extent of C_{org} storage in the poorly studied seagrass meadows of the Arabian Gulf. While there is relatively little carbon stored within the terrestrial biosphere of the Arabian Peninsula due to arid conditions, coastal environments may serve as critical and important carbon sinks within this region. Although seagrass communities in the Arabian Gulf are dominated by species of low stature and size (Price and Coles 1992), even these small-bodied species have been documented as significantly contributing to sediment stabilization (Christianen et al. 2013) and carbon storage (Lavery et al. 2013). Given that there are up to 10,000 km^2 of seagrasses in the Arabian Gulf (Erftemeijer and Shuail 2012), there is a large potential for these meadows to contain substantial stores of C_{org}. Thus, this study seeks to (1) further characterize the structure, abundance, and distribution of seagrasses across the poorly studied region of the Abu Dhabi coast, and (2) provide estimates of organic carbon stored in both living seagrass biomass and the underlying soils. Lastly, to place our findings within a larger context, we compare these data to estimates from global datasets, thus highlighting documented variation across meadows of varying structure (Lavery et al. 2013), and providing an increasingly accurate description of seagrass carbon stocks from underrepresented regions such as the Arabian Gulf.

Methods

Site Selection

The most extensive seagrass meadows in the Arabian Gulf are found along the coast of Abu Dhabi in the United Arab Emirates, which have been estimated to cover 5,500 km^2 (Erftemeijer and Shuail 2012; Phillips 2003). Carbon storage in seagrass meadows was measured at 18 sites, distributed along the coastline of Abu Dhabi on the southern shore of the Arabian Gulf, from Ras Muhayjij in the east to Ghurab NE in the west (Fig. 1). The sites were chosen to be representative of seagrass beds from a variety of energy regimes, from protected, muddy environments to exposed, sandy ones. All sites were sampled between 28 April and 7 May 2013. Water temperature and salinity data, as well as geographic location and water depth were recorded at all sites. Dive teams entered the water to accomplish three tasks: assessment of seagrass cover; collection of shallow, large-diameter cores for quantifying seagrass biomass; and collection of deeper cores to measure soil properties at the site.

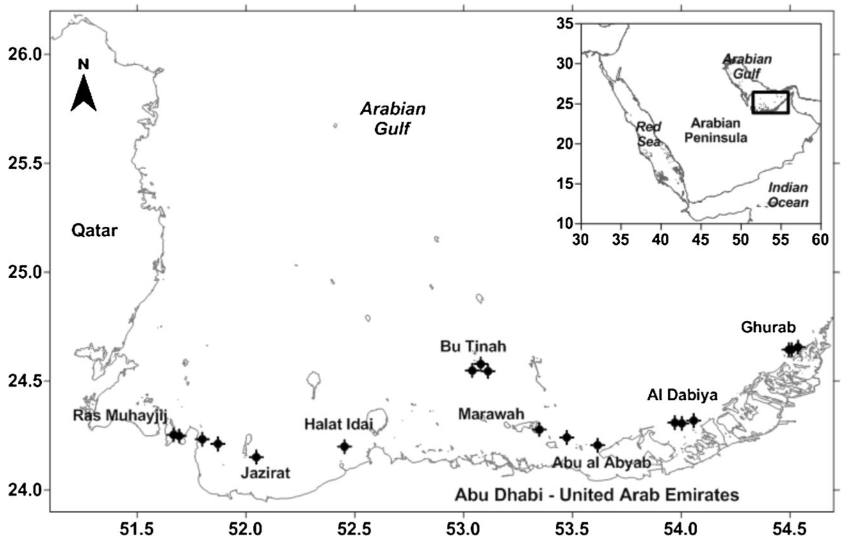

Fig. 1 Study area showing locations of seagrass survey sites along the Abu Dhabi coast

Seagrass cover and species composition was recorded at each coring site along a 50-m transect extending from a haphazardly dropped boat anchor. At 10 predetermined random distances along the transect, a 0.25-m^2 quadrat was placed on the bottom. All conspicuous benthic taxa in each quadrat were listed and given a cover score using a modified Braun–Blanquet scale (Fourqurean et al. 2001). Braun–Blanquet cover scores were later back-transformed to percent cover. Additionally, one oblique photograph was taken of each quadrat.

Seagrass biomass was collected with a 15-cm-diameter core tube inserted 40 cm into the substrate. 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 dried to a constant weight in a 50 °C oven and weighed.

Soil cores were collected at haphazardly selected locations within each site (duplicate or triplicate) by driving a diver-operated piston core into the soils until a depth of 1 m or refusal was reached. Subsequent processing of these cores followed the methods of Fourqurean et al. (2012b). These cores were returned to the boat, where they were subsampled at 3 to 9 cm intervals for the determination of dry bulk density (DBD), loss on ignition (LOI), and organic carbon content (C_{org}). These subsamples were 5.0 cm^3 transverse 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. During the field surveys, 40 soil cores were collected from 18 distinct seagrass meadows.

Measurement of the C Content of the Living Seagrass Biomass

Living seagrass tissues (including both aboveground and belowground components) were separated from the soil matrix, divided by species, and dried to a constant weight in a 50 °C oven. We converted these dry weight values to carbon equivalents assuming a carbon content of the seagrass biomass of 35 % of dry weight (Fourqurean et al. 2012a). We used the area of the core tube to calculate living seagrass carbon per unit area and expressed these values as megagram C per hectare.

Measurement of Organic C Content of Soil Samples

Each 5.0 cm^3 soil subsample was captured in a pre-weighted polyethelene 20 mL scintillation vial in the field and returned to the lab for processing. Samples were dried at 50 °C until constant weight was reached. DBD was calculated as the dry weight of the soil subsamples divided by the volume of the subsample (5 cm^3) and expressed as gram (dry weight) per cubic centimeter.

The dry subsamples were then homogenized by grinding them to a fine powder using a motorized mortar and pestle. Duplicate (ca. 1 g) aliquots of each soil sample were transferred to pre-weighed glass 20 cm^3 scintillation vials. These were then ashed in a furnace at 500 °C for 6 h until constant weight was reached. For each subsample, LOI was calculated as:

$$\mathrm{LOI} = \frac{\text{Initial dry weight} - \text{weight remaining after ashing}}{\text{Initial dry weight}} \times 100\%$$

We measured total carbon ($\mathrm{TC}_{\mathrm{soil}}$) content of duplicate 30 mg aliquots of the dry soil subsamples using an automated elemental analyzer (Fisons NA1500). In order to measure the C_{org} content of the soil samples, we used the instrumental analyzer-dry oxidation procedures described by Fourqurean et al. (2012a). Briefly, the inorganic carbon content of the ash ($\mathrm{IC}_{\mathrm{ash}}$) remaining after the LOI measurements was determined using the elemental analyzer; this $\mathrm{IC}_{\mathrm{ash}}$ value was scaled back to the original weight of the unashed sample using the LOI to calculate the inorganic carbon content of the original soil (IC_{soil}). We then calculated C_{org} (expressed in units of % of dry weight) as:

$$C_{org} = TC_{soil} - IC_{soil}$$

While it has been reported that LOI may lead to an over estimation of C_{org} in carbonate-rich soils, prior analyses of soil samples (whereby both LOI and C_{org} were directly determined) indicate a tight correlation between these metrics (Fourqurean et al. 2012a, supplementary material). LOI was not a good proxy for C_{org} at low LOI values (<0.52 %). Within our survey, mean LOI of Abu Dhabi soils was 3.75 %, with a minimum and maximum of 1.57 and 10.7 %, respectively.

Calculation of Areal C_{org} Storage

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

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

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, multiplied by 100 to convert C_{org} units from percent of dry weight to gram C per gram dry weight. We obtained an estimate of the precision of our calculated CC per slice using the standard estimate for propagation of errors in the product of two numbers:

$$\sigma_{CC} = CC_{slice} \times \sqrt{\frac{\sigma_{DBD}}{DBD}^2 + \frac{\sigma_{Corg}}{Corg}^2}$$

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, σDBD is the standard deviation of the DBD values, and σ_{Corg} is the standard deviation of the C_{org} values in each slice.

C_{org} density of the soils at a site was calculated as the sum of the CC_{slice} values for all of the slices in the core:

$$\text{Carbon density} = \sum_{i=1}^{n} CC_i$$

Where *i* represents each core slice and *n* represents the total number of 10 cm slices from each site. C_{org} density was converted to units of megagram C per hectare. Estimates of the standard deviation of the C_{org} density ($\sigma_{\text{Carbon density}}$) for each site were calculated using the standard method for propagation of errors in a summation:

$$\sigma_{\text{Carbon density}} = \sqrt{\sigma_{0\text{–}10}{}^2 + \sigma_{10\text{–}20}{}^2 + \sigma_{20\text{–}30}{}^2 + \ldots \sigma_{90\text{–}100}{}^2}$$

Where, for example, $\sigma_{0\text{–}10}$ is the σ_{CC} for the 0–10 cm slice. We assumed that our cores penetrated through all of the soil at a site to a depth of 1 m or until underlaying rock was encountered. We further assumed that the underlying rocks had no organic C content. We report C_{org} density of the entire cores, and also C_{org} storage in the top m, 50 cm, and 10 cm of soil.

Results

Water depths at the selected sites ranged from 2.7 to 14.0 m (Table 1). Salinity of the overlying water column decreased from ca. 46.6 in the west to ca. 42.5 in the east. There was no spatially coherent pattern in water temperatures, which averaged 26.6±0.3 °C (±1 SEM) and ranged from 25.0 to 28.3 °C.

Across the 18 selected sites, three species of seagrass were encountered: *Halodule uninervis* ((Forsskäl) Ascherson), *Halophila ovalis* (Brown), and *Halophila stipulacea* ((Forsskäl) Ascherson). 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 2). *Halodule uninervis* was the most commonly encountered seagrass; it was present at all 18 survey sites. *Halophila ovalis* was absent from 1 of the 18 sites, while its congener *Halophila stipulacea* was only found at 11 of the 18 sites. Notably, *Halophila stipulacea* was absent from the easternmost sample area. Despite its common distribution, *Halophila ovalis* was never found in high abundance, rarely exceeding 10 % cover. Only one monospecific seagrass bed was recorded (Ghurab NN), where *Halodule uninervis* was present in low abundance (8.5 %). Carbon stored in the living biomass of Abu Dhabi seagrass beds was relatively modest, ranging from 0.03 to 1.13 Mg C ha^{-1} with a mean of 0.4±0.1 (±1 SEM) (Table 2).

Our soil cores penetrated from a minimum of 8.5 cm to a maximum of 100 cm (Table 1). The soils underlying the seagrass beds of the Arabian Gulf in Abu Dhabi were mainly silty sands with DBD that ranged from a minimum of 0.49 to 1.82 g cm^{-3}, with a mean of 1.37±0.04 g cm^{-3}, based on 471 subsamples collected from the 18 seagrass sampling sites. Values of DBD were normally distributed, with a median value of 1.39 (Fig. 2). In general, DBD increased with depth in the top 15 cm of the cores. Below that depth, DBD showed no overall pattern down-core. The inorganic fraction of the soils was predominantly composed of calcium carbonates. IC ranged from 6.95 to 11.57 % of dry weight, with a mean of 10.15±0.04 %. Assuming that all of this IC was in the form of

Table 1 Location and physical characteristics of seagrass carbon storage survey sites. Soil depths are means of multiple measurements (*n*=1–3)

Site name	Latitude (°N)	Longitude (°E)	Soil depth (cm)	Water depth (m)	Salinity (PSU)	Temperature (°C)
Ras Muhayjij	24.25277	51.66758	49.0	7	nd	nd
Dahwat an Nahklah	24.24782	51.69347	84.0	4.6	46.6	25.3
Sila peninsula	24.23258	51.79963	29.0	14	45.3	25.4
Umm Al Hatam	24.21152	51.87123	70.0	6.1	45.2	25.4
Jazirat	24.15132	52.0476	45.3	5	45.4	25.4
Halat Idai	24.19905	52.45295	16.2	8.9	45.1	25.4
Bu Tinah 3	24.54852	53.03997	53.8	5.2	43.4	27.4
Bu Tinah 2	24.57855	53.079	97.8	2.7	43.6	27.4
Bu Tinah SE	24.54534	53.11234	35.0	6.1	43.2	27.2
Marawah	24.27702	53.34829	44.2	6.4	44.9	26.8
Fasht al Basm	24.24085	53.47422	69.5	2.7	44.8	28.1
Abu al Abyab	24.20513	53.61585	88.5	4.6	46.3	28.3
Al Dabiya 1	24.30876	53.97083	8.5	4.6	43.8	27.8
Al Dabiya 2	24.30582	54.00273	34.0	4	43.8	28
Al Dabiya 3	24.31826	54.05725	98.8	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	34.5	6.1	42.3	25.9
Ghurab NE	24.65578	54.53673	32.3	6.1	42.7	25

Table 2 Seagrass bed percent composition and total carbon stored per hectare seagrass biomass (Mg C ha^{-1}). Percent composition was calculated from visual quadrats (*n*=10) at each site. Total seagrass biomass was calculated from a single large diameter core collected at each site

Site name	Seagrass canopy height (cm)	*Halodule uninervis* Cover (%)	*Halophila ovalis* Cover (%)	*Halophila stipulacea* Cover (%)	Sum of seagrass cover Cover (%)	Total seagrass biomass Mg C 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	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	15.7	0.13
Marawah	8	11.3	2.5	2.5	16.3	0.12
Fasht al Basm	9	24.9	2.5	8.4	35.7	0.82
Abu al Abyab	17.9	60	6.7	20.2	86.9	0.73
Al Dabiya1	7.4	41.4	2.5	0	43.9	0.83
Al Dabiya2	8.4	65	2.5	0	67.5	1.13
Al Dabiya3	10.8	50	3.5	0	53.5	0.4
Ghurab N	5	22.4	2.5	0	24.9	0.17
Ghurab NN	6.8	8.1	0	0	8.1	0.21
Ghurab NE	8.2	17.3	4.9	0	22.2	0.43
Mean	8.1	23.7	3.8	8.8	36.2	0.4
SEM	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	2.5	0	0	7.5	0
Max	17.9	65	9.3	62.5	86.9	1.1

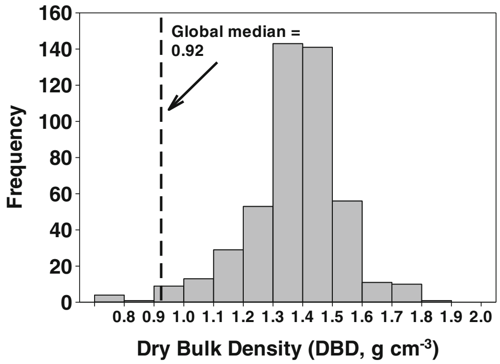

Fig. 2 Frequency histogram of dry bulk density (DBD g cm^{-3}) in Abu Dhabi soils (n=477). The *dashed line* represents the median value of DBD from the global dataset of Fourqurean et al. (2012a)

$CaCO_3$, which has an IC content of 12 %, the soils ranged from 57.9 to 96.4 % calcium carbonate, with a mean of 84.6± 0.5 %. These values largely reflect the calcareous composition of the sediment matrix within this region (Kenig et al. 1990).

Organic content (C_{org}) of the soil samples ranged from below detection (less than 0.05 %) to a maximum of 2.44 % (n=469). The mean C_{org} was 0.64±0.39 %, but values were not normally distributed (Fig. 3). The data distribution was truncated at zero and had relatively few high values; the median C_{org} was 0.58 %. Down-core profiles in C_{org} displayed variable trends. To facilitate comparisons, we classify cores into relatively shallow (<40 cm) and relatively deep (>40 cm) cores based upon documented differences in soil characteristics (shifts in C_{org} decay rates) at this depth (Serrano et al. 2012). Deeper cores (>40 cm) revealed general declines in C_{org} with increasing core depth (Fig. 4), however note exceptions at the Umm Al Hatam, Bu Tinah SE, and Marawah sites. Meanwhile, shallower cores (<40 cm) displayed increasingly variable trends, with some sites showing declines in C_{org} with depth (Al Dabiya 2, Ghurab NN), while others show no overall trend (Halat Idai, Al Dabiya 1, Ghurab N) (profiles not shown).

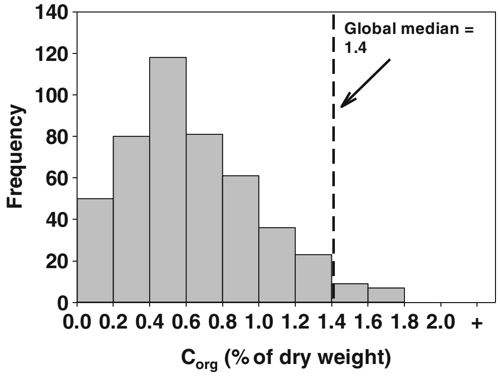

Fig. 3 Frequency histogram of organic carbon content (C_{org}, % dry weight) in Abu Dhabi soils (n=477). The *dashed line* represents the median value of C_{org} from the global dataset of Fourqurean et al. (2012a)

Total C_{org} stored in the soils of Abu Dhabi seagrasses ranged from a minimum of 1.9 Mg C ha^{-1} at Al Dabiya 1 to a maximum of 109.0 Mg C ha^{-1} at Umm al Hatam (Table 3, Fig. 5). Mean C stores across the 18 sites sampled was 49.1± 7.0 Mg C ha^{-1}. There was no significant relationship between the abundance of seagrasses, assessed either as percent cover or living plant biomass, and soil carbon stores (Fig. 6).

Discussion

Seagrasses are widely distributed along the Abu Dhabi coast (Erftemeijer and Shuail 2012; Phillips 2003), and the soils that underlay those seagrasses contained appreciable stores of C_{org}. When compared to literature estimates of C_{org} storage in seagrass beds worldwide (Fourqurean et al. 2012a), the C_{org} stores at our survey sites were low on an areal basis, but because of the extensive seagrass distribution and the low storage of C_{org} in the desert land areas, seagrass meadows are a relatively large C_{org} store in this region. It has been estimated that there are 5,500 km^2 of seagrass habitat across the waters of Abu Dhabi, and up to 10,000 km^2 of seagrasses across the entire Arabian Gulf (Erftemeijer and Shuail 2012). Multiplying these areas by the mean C_{org} found in living seagrass biomass (0.4 Mg C ha^{-1}) yields a total estimate of 220±108 Gg C (±95 % CI) of living C_{org} in Abu Dhabi seagrasses, and 400±196 Gg C (±95 % CI) across the entire Arabian Gulf. These values are small compared to the amount of C_{org} stored in the top meter of soils below these seagrasses, which we estimate to be 27.0±7.5 Tg C (±95 % CI) in Abu Dhabi waters and 49.1±13.7 Tg C (±95 % CI) across the entire Arabian Gulf. The total C_{org} stored in Abu Dhabi's seagrass beds is roughly 70 % of the total annual CO_2 emissions as reported by AlFarra and Abu-Hijleh (2012).

We found extensive seagrass meadows in our surveys, with most supporting more than one seagrass species. Both *Halophila ovalis* and *Halodule uninervis* had the widest spatial distribution, whereas *Halophila stipulacea* was limited to the central and western sites. The seagrasses of Abu Dhabi displayed low living biomass relative to other locations. Mean C_{org} stores in seagrass biomass were 0.4±0.1 Mg C ha^{-1}, as compared to the global average of 2.51±0.49 Mg C ha^{-1} (Fourqurean et al. 2012a). Such distinctions are driven by the relatively small size and low stature of seagrasses within the Arabian Gulf. Comparatively, seagrass meadows that are comprised of large-bodied, longer lived species such as *P. oceanica* from the Mediterranean tend to have living C_{org} stores that are an order of magnitude higher, attributable to both higher above and belowground biomass. Across our selected sites, total seagrass biomass was strongly correlated to the areal percent coverage of *Halodule uninervis*, suggesting that the presence of this larger species drives spatial variation in living C_{org} stores in this region.

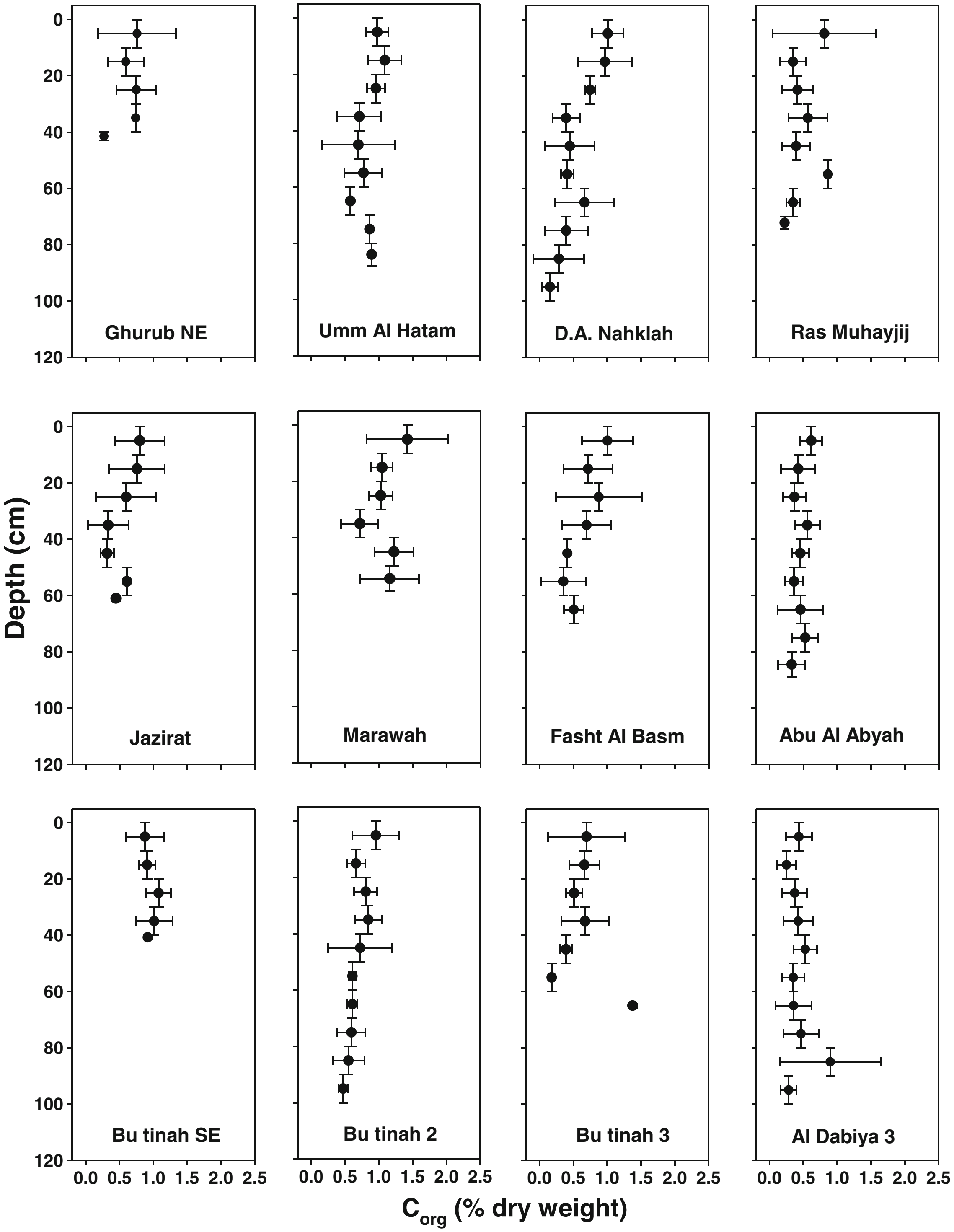

Fig. 4 Down core profiles of soil C_{org} (means±1SEM, n=1–3). Only sites with cores ≥40 cm are displayed

Compared to literature values for global seagrass beds (Fourqurean et al. 2012a), DBD values in these samples were relatively high (Fig. 2), especially given the carbonate mineralogy of the Abu Dhabi soils (Kenig et al. 1990). 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. 2012a). Interestingly, the DBD values we observed were more similar to values from those observed in seagrass beds dominated by siliceous sediments of terrestrial origin (Fourqurean et al. 2012a), despite the fact that the Abu Dhabi soils were 57.9 to 96.4 % by weight calcium carbonate. Relatively low C_{org} values from our soils also increased DBD since organic matter

Table 3 Summary of soil C_{org} stocks (Mg C ha^{-1}). Estimates from the upper 10 cm, 50 cm, and 1 m of soil are displayed to facilitate comparisons with other studies that predominantly report values from shallower cores (Fourqurean et al. 2012a)

Site name	Mean core depth cm	Cores per site	Subsamples per core	Soil C stock top m		Soil C stock top 50 cm		Soil C stock top 10 cm	
				Mg C ha^{-1} mean	sd	Mg C ha^{-1} mean	sd	Mg C ha^{-1} mean	sd
Ras Muhayjij	49.0	2	8, 18	61.1	17.9	38.8	17.7	10.4	14.1
Dahwat an Nahklah	84.0	2	15, 19	65.4	16.8	39.8	10.5	10.2	3.4
Sila peninsula	29.0	2	6, 13	18.8	5.8	18.8	5.8	6	3.8
Umm Al Hatam	70.0	2	12, 16	109	16.5	63.9	15.3	12.8	3.3
Jazirat	45.3	3	12, 13, 15	50.2	15.6	39.5	15.6	10.9	7.1
Halat Idai	16.2	3	5, 6, 6	13.2	8.4	13.2	8.4	6.8	6.9
Bu Tinah 3	53.8	2	13, 15	46.7	13.9	41.1	13.9	9.2	10.7
Bu Tinah 2	97.8	2	22, 22	91.7	13.8	50.8	12	11.7	6
Bu Tinah SE	35.0	2	10, 14	52.2	8.3	52.2	8.3	10.9	4.9
Marawah	44.2	3	8, 13, 14	74.2	13.8	60.2	11.6	13.2	8.3
Fasht al Basm	69.5	2	16, 18	61.4	18.6	49.9	17.3	13.1	7
Abu al Abyab	88.5	2	20, 20	58	12.3	34.2	8.3	8.1	3
Al Dabiya1	8.5	2	2, 3	8.1	3	8.1	3	8.1	3
Al Dabiya2	34.0	2	9, 12	29	7.6	29	7.6	9.8	3.5
Al Dabiya3	98.8	2	20, 24	78.9	19.6	28.3	8.2	6.1	3.8
Ghurab N	8.5	1	3	1.9	1.7	1.9	1.7	1.9	1.7
Ghurab NN	34.5	2	8, 9	22.4	11	22.4	11	8.3	5.2
Ghurab NE	32.3	2	7, 8	41.2	13.9	41.2	13.9	10.6	11.4
Mean				49.1	12.1	35.2	10.6	9.3	5.9
SEM				7	1.2	4.1	1.1	0.7	0.8
Median				51.2	13.8	39.2	10.8	10	5.1
Min				1.9	1.7	1.9	1.7	1.9	1.7
Max				109	19.6	63.9	17.7	13.2	14.1

has a much lower particle density than mineral grains. Compared to values of C_{org} composition from seagrass beds around the world (Fourqurean et al. 2012a), Abu Dhabi seagrass soils had relatively low C_{org} (Fig. 3). The global average C_{org} from seagrass beds ranges between 0 and 48.2 %, with a mean of 2.0±0.1 % (Fourqurean et al. 2012a). The average soil C_{org} measured in Abu Dhabi seagrasses was 0.64±0.39 %, comparable to values from temperate seagrass meadows in siliceous mineral environments dominated by the seagrass *Zostera marina* (Krause-Jensen et al. 2011; Townsend and Fonseca 1998).

Because of the low C_{org} content of the soils, total soil C_{org} stores were relatively low at our sites as compared to the

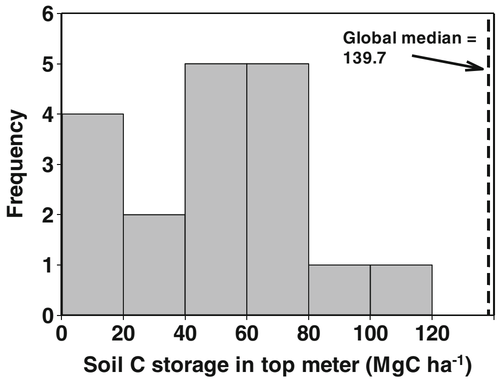

Fig. 5 Frequency histogram of carbon storage in top meter of soil (Mg C ha^{-1}) in Abu Dhabi soils (n=18). The *dashed line* represents the median value of carbon storage in top meter of soil from the global dataset of Fourqurean et al. (2012a)

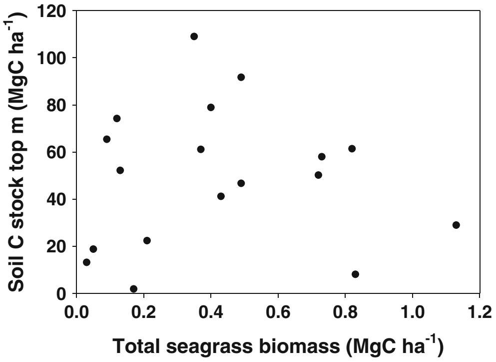

Fig. 6 Relationship between seagrass biomass and soil C_{org} stores across all sites

global average. As integrated over the top meter of soil, C_{org} stores in Abu Dhabi averaged 49.1 Mg C ha^{-1}, whereas global estimates average 194.2 Mg C ha^{-1}. Some of the highest regional estimates in seagrass soil C_{org} stocks are from the Mediterranean (372.4 Mg C ha^{-1}) and South Australia (268.3 Mg C ha^{-1}). The low soil carbon storage in our study resulted from a combination of both limited soil thickness at our sites, and relatively low C_{org} concentrations in the soil. Sites such as Ghurab N, Al Dabiya 1, and Halat Idai all contained core depths <20 cm, largely restricting soil C_{org} stocks at those locations. Interestingly, the Al Dabiya region within the eastern portion of our survey contained sites with some of the shallowest and thickest soil deposits. Furthermore, the site in this region with the lowest total seagrass biomass displayed the deepest core depth and highest soil C_{org} stock, suggesting that carbon storage within seagrass beds may be strongly influenced by site depositional and geomorphological characteristics that are independent of seagrass cover.

Down-core soil profiles generally followed expected trends, with decreases in C_{org} content at increasing depth. However, there were several exceptions. These patterns likely result from typical processes of organic carbon remineralization, whereby initial losses are mainly derived from the labile carbon pool, leaving behind increasingly refractory material (Burdige 2007; Serrano et al. 2012). Similar trends in soil C_{org} have been documented from deep cores (>1 m) in Florida Bay (Fourqurean et al. 2012b) and the Mediterranean (Serrano et al. 2012). Such trends from deeper cores are further characteristic of soils that experience relatively little turnover. Thus, our sites with shallower cores may not display these trends due to potentially higher rates of sediment mixing.

There was no significant relationship between seagrass abundance (assessed as either percent cover or living biomass) and soil carbon stores. This may result from the broad subtidal area within the coastal zone that supports ephemeral seagrass patches that move across the surface soils as they expand one edge of the meadow and erode away at the other. Thus, temporal variation in seagrass coverage at any given location may limit a strong correlation between present seagrass abundance and soil C_{org} stores. The waters of the Arabian Gulf are subject to rather large variations in salinity and temperature (Erftemeijer and Shuail 2012; Price and Coles 1992), and these conditions contribute to the presence of opportunistic, short-lived species that recover quickly and rapidly recolonize open substrate. Furthermore, it is important to stress the influence of abiotic, geomorphological site characteristics in determining soil C_{org} stores, as temperature, water depth, exposure, and wave energy can all serve to alter the depositional environment (Lavery et al. 2013; Pedersen et al. 2011). The ephemeral nature of these seagrass meadows, combined with other geomorphological site characteristics that influence the deposition of organic matter, may largely contribute to the discrepancy between soil carbon stocks and seagrass biomass.

Despite the relatively low stores of living and soil C_{org}, seagrass meadows of Abu Dhabi play a significant role in carbon storage within this region. Estimated over the top meter, mean soil carbon stocks were 49.1 Mg C ha^{-1}, comparable to literature estimates from seagrass meadows of the North Atlantic (48.7 Mg C ha^{-1}) and Indopacific (23.6 Mg C ha^{-1}) (Fourqurean et al. 2012a). While this value is small compared to other terrestrial systems (i.e., temperate forests with an estimated 300 Mg C ha^{-1}), we submit that seagrass meadows (along with other coastal vegetation) represent some of the largest C_{org} stocks within this arid region.

Recent work by Lavery et al. (2013) demonstrate that even seagrass meadows comprised species with relatively low stature and biomass can contribute to carbon storage. While also potentially attributable to depositional environment, they document similar levels of soil C_{org} stocks between seagrass meadows comprised of either large-bodied *Posidonia australis* or small-bodied *Halophila ovalis*. Thus, despite limited canopy structure and belowground biomass, smaller seagrasses may still facilitate carbon storage via reductions in sediment erodability (Christianen et al. 2013) and increases in suspended particle trapping (Fonseca and Cahalan 1992; Paul et al. 2012).

Our results contribute to the existing global database on seagrass meadow C_{org} storage, and suggest that even meadows comprised of ephemeral seagrass species can play an important role in carbon sequestration and Blue Carbon initiatives. We argue that research targeting poorly represented coastal habitats will likely highlight the need to conserve and restore these environments as viable strategies for the mitigation of anthropogenic carbon emissions. Many marine environments within the Arabian Gulf face threats from coastal development and land-use alterations (Erftemeijer and Shuail 2012; Sheppard et al. 2010). Industrial development, land reclamation, desalination, and oil exploration all serve to affect the health and integrity of coastal seagrass meadows, posing significant challenges to current and future rates of carbon burial (Pendleton et al. 2012).

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