

RESEARCH ARTICLE

# Carbon storage in the seagrass meadows of Gazi Bay, Kenya

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## Abstract

Vegetated marine habitats are globally important carbon sinks, making a significant contribution towards mitigating climate change, and they provide a wide range of other ecosystem services. However, large gaps in knowledge remain, particularly for seagrass meadows in Africa. The present study estimated biomass and sediment organic carbon ( $C_{org}$ ) stocks of four dominant seagrass species in Gazi Bay, Kenya. It compared sediment  $C_{org}$  between seagrass areas in vegetated and un-vegetated ‘controls’, using the naturally patchy occurrence of seagrass at this site to test the impacts of seagrass growth on sediment  $C_{org}$ . It also explored relationships between the sediment and above-ground  $C_{org}$ , as well as between the total biomass and above-ground parameters. Sediment  $C_{org}$  was significantly different between species, range: 160.7–233.8 Mg C ha<sup>-1</sup> (compared to the global range of 115.3 to 829.2 Mg C ha<sup>-1</sup>). Vegetated areas in all species had significantly higher sediment  $C_{org}$  compared with un-vegetated controls; the presence of seagrass increased  $C_{org}$  by 4–6 times. Biomass carbon differed significantly between species with means ranging between 4.8–7.1 Mg C ha<sup>-1</sup> compared to the global range of 2.5–7.3 Mg C ha<sup>-1</sup>. To our knowledge, these are among the first results on seagrass sediment  $C_{org}$  to be reported from African seagrass beds; and contribute towards our understanding of the role of seagrass in global carbon dynamics.

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## Introduction

Carbon sinks in terrestrial ecosystems are better studied than those in marine plant communities. However, the global importance of vegetated coastal habitats as carbon sinks has become appreciated over the last decade [1]. These ‘blue carbon’ ecosystems (tidal marshes, mangroves and seagrass meadows) have recently been demonstrated to capture and store huge stocks of carbon, and their management and conservation may play an important part in global climate change mitigation strategies [2,3,4,5]. Although they occupy less than 2% of the world’s ocean surface area [6], blue carbon ecosystems are estimated to bury nearly 27.4 Tg C yr<sup>-1</sup> which is about 10% of the yearly estimated organic carbon ( $C_{org}$ ) burial in the oceans [7]. Unlike many terrestrial systems that store  $C_{org}$  primarily in living biomass, vegetated coastal ecosystems store much of their  $C_{org}$  stock in the sediment, which may produce carbon sinks of hundreds

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to thousands of years age [7]. However, this stored  $C_{org}$  risks being released back to the atmosphere when blue carbon ecosystems are degraded [7].

Seagrass meadows are the most extensive of the blue carbon ecosystems, with an estimated global surface area of between 300,000 to 600,000 km<sup>2</sup> [1,7]. Despite this wide spatial coverage seagrasses are the least well-studied blue carbon ecosystem. They provide important ecosystem services that include: support for commercial fisheries, worth \$ 3500 ha<sup>-1</sup> yr<sup>-1</sup> [8], and subsistence fisheries [9], sediment stabilization [10], improved water quality and light availability [11,12] and nutrient cycling (estimated to be worth \$ 3.8 trillion yr<sup>-1</sup> globally [13]). In addition, seagrasses are recognized as one of the most efficient carbon sinks on the planet [3]. Seagrass meadows store about twice as much  $C_{org}$  per unit area as soils in productive temperate and upland tropical forests, and provide a global carbon sink of approximately 19.9 Pg [3,14]. This is approximately equal to the combined amount of  $C_{org}$  stored in the world's tidal marshes and mangrove forests which is estimated at 10 Pg [15]. An estimated 50% of the  $C_{org}$  buried in seagrass meadows' sediment is thought to be of external origin [4]. The dense canopies of seagrasses reduce water flow velocity, thus promoting the trapping and deposition of sediment and particles from the water column [16,17]. Analysis of a global data set revealed that the mean seagrass biomass  $C_{org}$  was  $2.52 \pm 0.48$  Mg  $C_{org}$  ha<sup>-1</sup> ( $\pm 95\%$  CI), while sediment  $C_{org}$  was estimated to account for between 0.002–48% of the sediment dry weight [3]. However, these findings may be inaccurate considering the uneven distribution of research into seagrass carbon budgets globally and the large variation recorded between different sites. Much of the information on seagrasses, especially on sediment  $C_{org}$ , is from Mediterranean and Australian seagrass beds [1,2,7]. Past global reviews of seagrass carbon acknowledged the disproportionately low contribution of data from the African continent [3,18]. A recent review of seagrass biomass and productivity in Africa found no published estimates of seagrass sediment carbon from the continent [19]. Seagrass beds are suffering rapid global decline; almost a third of all seagrass areas are thought to have been lost in the last 140 years [20] and current rates of loss are estimated at around 1.5% year<sup>-1</sup> [21]. This implies that a significant amount of the stored  $C_{org}$  could soon be remineralized and that the potential for future carbon capture is being diminished, undermining efforts to mitigate climate change [3]. However, the amount of carbon that could be remineralised at a global scale remains highly uncertain. This is because: first, the vulnerability of this stored carbon to ecosystem change and degradation is little studied (with one recent paper showing surprising persistence of buried carbon following seagrass removal [14]). Second, the huge gaps in knowledge on the extent and quantity of the global seagrass carbon sink make global estimates very imprecise. Improving our knowledge of carbon storage and burial rates in seagrass ecosystems, of how these variables differ between sites and of the controls on burial rates and sink sizes is fundamental in achieving a better understanding of how seagrass meadows may contribute to slowing global warming.

Whilst previous seagrass studies in Gazi Bay have focused on species distribution, community composition, growth dynamics, nutrient content and carbon export between the seagrasses and the adjacent ecosystems [19–26], no study here (or elsewhere in Africa) has considered the carbon stocks and how these might compare with naturally occurring un-vegetated areas. The current work aimed to fill this gap by estimating the carbon stocks in the seagrass meadows of Gazi Bay, Kenya. At the same time, the work explored whether different seagrass  $C_{org}$  pools could be estimated using easy to measure parameters such as the above-ground biomass (AGB) and shoot height. Specifically, the objectives of the study were:

1. To compare sediment  $C_{org}$  between areas with seagrass and adjacent un-vegetated areas for each of the four dominant seagrass species in order to estimate the impact of these species on sediment carbon storage.

2. To determine the %  $C_{org}$  associated with each of the four dominant seagrass species at Gazi Bay and the relative contribution of biomass and sediment to the  $C_{org}$  per unit area of the seagrass species as well as their relationship to the above-ground parameters.
3. To explore the relationships between sediment  $C_{org}$  and the above ground carbon (and also above-and belowground biomass ratios for the dominant seagrass species of Gazi Bay.

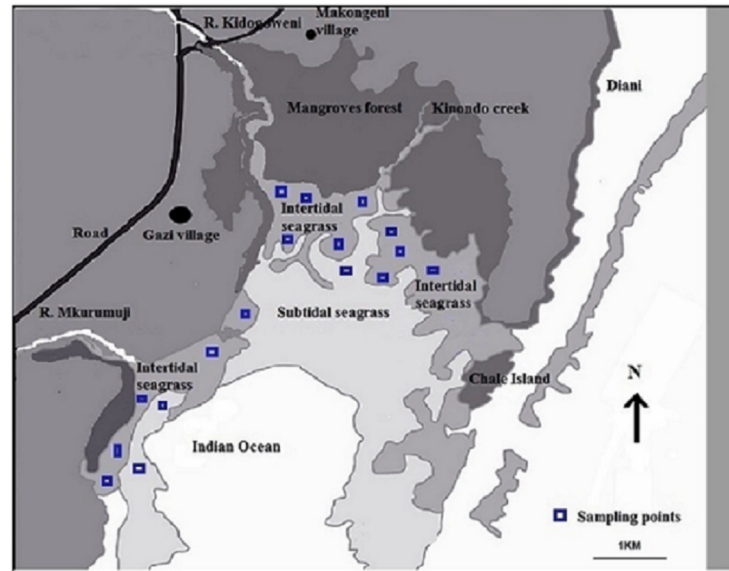
## Materials and methods

### Study site

This study was carried out at Gazi Bay (4° 25'S, and 39° 30'E), located on the southern coast of Kenya, about 55 km from Mombasa City through permission issued by the National Commission for Science, Technology & Innovation (NACOSTI): Permit no NACOSTI/P/14/2443/769 on 17<sup>th</sup> February 2014. The bay is a shallow tropical coastal water system (mean depth < 5m), approximately 1.75–3.5 km wide and 3.25 km long with a surface area of ~ 17 km<sup>2</sup> [22]. It is open to the Indian Ocean through an entrance in the south with depths varying between 3 and 8m in the eastern and western regions respectively [27]. It is characterized by two creeks, a western creek that extends to a fresh water inflow (R. Kidogweni) on the north western side of the bay and an eastern creek that lacks such an inflow. On the south western side of the bay is another fresh water inflow from R. Mkurumuji (Fig 1).

The main climatic drivers are the southeast monsoons (May-September) and the northeast monsoons (November-March). An offshore wind prevails throughout the year. Long rains occur between March and May while the short rains occur between October and November [27,28]. However, inter-annual shifts in these seasons are common [29]. The tide at Gazi Bay is normally mixed semi-diurnal, with a tidal range of 1.4 m and 3 m at neaps and springs respectively. These tides generate strong reversing currents in the tidal creeks and relatively weaker currents in the open regions of the bay. The shoreward wind and the tidal currents combine to vertically mix the water column in the bay, leading to formation of a more homogeneous water, with a salinity range of 34.5–35.5ppt. A significant lateral and vertical salinity gradient develops during the rainy periods as a result of increased river discharge and the runoff [27]. The flushing ability of mixed semi-diurnal tides in the bay varies depending on tidal range, tidal elevation, and the nature of the tide. Tides are generally swift during springs and tend to rapidly disperse lower salinity water [27,30]. The rates of water exchange are also high during spring tides compared to neap tides. On the other hand, currents at neaps are sluggish and inhibit flushing of brackish water. This flushing pattern of the tide combined with river runoff has a far-reaching effect in the form of nutrient and material exchanges on the linkage between mangrove, seagrass, and coral reef ecosystems [30–32]. Seagrasses, which are found at the centre of the bay, cover an area of ~ 7 km<sup>2</sup> [21,26,28].

All the twelve seagrass species described along the East African coast have been recorded in Gazi Bay, usually attached to both soft and hard substrates in the bay [33–35]. The seagrass community in the bay consists of four dominant species: *Thalassodendron ciliatum* (Forssk.) den Hartog, *Thalassia hemprichii* (Enhrenberg) Aschers., *Enhalus acoroides* (L.f.) Royle and *Syringodium isoetifolium* (Aschers.) Dandy. These are observed to grow either as monospecific stands or mixed with other seagrass species, with their coverage extending from the intertidal to the subtidal areas in sandy and rocky substrates [22]. The other, less abundant species, are: *Cymodocea rotundata* Ascherson, *Cymodocea serrulata* (R. Braun) Aschers. & Magnus, *Halodule uninervis* (Forssk.) Aschers., *Halodule wrightii* (Aschers.), *Halophila minor* (Zoll.) den Hartog, *Halophila ovalis* (Braun) Hooker, *Halophila stipulaceae* (Forssk.) Aschers. and *Zostera*



**Fig 1. Seagrass sampling points in the seagrass meadows of Gazi Bay, Kenya.**

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*capensis* (Setch) [22,35]. The meadows are usually luxuriant for most of the year except during short periods of intense grazing and desiccation. The seagrass meadows of Gazi Bay fall under Diani-Chale Marine National Reserve which was established in 1994. It also forms the northern boundary of the proposed Transboundary Marine Conservation Area between Kenya and Tanzania (TBCA) [36]. At present there is no enforcement of its protected status due to weak governance. The use of seine and drag nets by artisanal fishermen is a daily activity in the shallow waters of the bay. Although there are no published data on the effects of this fishing, anecdotal information and personal observation suggests this is a cause of degradation of the seagrass in areas of intense fishing.

### Sampling design

We used sampling procedures specific for coastal blue carbon and the revised Intergovernmental Panel for Climate Change (IPCC) carbon accounting protocols for coastal wetlands [37,38]. Intensive studies were made within mono-specific stands of four seagrass species: *T. hemprichii*, *E. acoroides*, *T. ciliatum* and *S. isoetifolium*. These species were selected on the basis of their local dominance, as determined by the initial reconnaissance survey carried out by the team. Samples were taken from a wide area following a stratified random design, which extended from plots adjacent to the mangrove forest, all the way to the seagrasses near the mouth of the R. Mkurumuji (Fig 1), in order to sample the spatial variability of biomass and sediment  $C_{org}$  associated with the four target species in the bay. Forty quadrats, each measuring  $0.25\text{ m}^2$ , were sampled for the biomass carbon for each of the three species, *T. hemprichii*, *E. acoroides* and *T. ciliatum* whilst 20 quadrats were sampled for *S. isoetifolium*, owing to its relatively small spatial distribution.

### Determination of species type, canopy cover, shoot density and canopy height

Sample plots were established within the identified seagrass strata placing the quadrats of  $0.25\text{ m}^2$  at minimum intervals of 15m in each seagrass strata. This was done during low spring

tides since at this time the seagrass beds are exposed and accessible on foot. Species type was determined *in situ* with the help of field manuals [39]. Shoot density and canopy cover were determined by counting all the shoots within quadrats and extrapolating to per m<sup>2</sup> while the % canopy cover was obtained through visual estimates. Canopy height was determined through the measurement of heights of 10% of randomly selected individual shoots from the total within the quadrat and calculating the mean heights.

### Estimation of above-ground and below-ground biomass

The above-ground biomass (AGB) was obtained by harvesting all plant materials above-ground within the 0.25m<sup>2</sup> quadrats. In the laboratory, the seagrass was cleaned with fresh water, sorted and scraped with a razor blade to remove epiphytes. Seagrass fronds were then washed in 10% hydrochloric acid to remove any calcareous material after which they were dried in an oven at 60°C for 72 hours. For below-ground biomass, four cores were taken in each of the four quarters of the 0.25m<sup>2</sup> quadrats with a Russian peat sampler (50cm long and 5cm diameter). Initial washing was done in the field using a 500µm sieve. In the laboratory further washing and rinsing of the samples was carried out. Upon sieving, the materials were sorted into component parts: roots, rhizomes and necromass (that is dead roots or rhizomes) and dried in an oven at 60°C for 72 hours. The combined below-ground biomass values for the roots, rhizomes and necromass from the four cores per quadrat were summed and then converted to per m<sup>-2</sup>. The total biomass carbon was obtained by multiplying biomass with a carbon conversion factor of 0.34 (assuming that carbon constitutes 34% of the biomass) and then extrapolated to per hectare following recommended protocols for estimating carbon for marine ecosystems [37,38].

### Measurements of bulk density, % organic matter and sediment C<sub>org</sub>

Two sediment cores, each extending to a depth of 50cm, were collected in each quadrat, using the peat sampler from the vegetated and the un-vegetated areas, chosen to act as natural ‘controls’ for each species. Vegetated areas were identified as those with seagrass cover while un-vegetated areas were the naturally occurring bare patches, measuring 3 to 6m in diameter, in the midst of the seagrass covered areas.

In the laboratory, the samples were sliced into 5cm sub-sections and were oven dried at 60°C for 72 hours to obtain a constant weight. Similar cores were collected in un-vegetated seagrass areas to serve as ‘controls’.

Dry bulk density (DBD) (the dry weight of sediment per unit volume) was calculated for each of the ten sub-sections per core as follows:

$$DBD (g/cm^3) = \text{Dry weight} / \text{Original volume of the sediment}$$

Organic matter was measured in each of the ten sub-sections per core by Loss on Ignition (LOI) techniques, using a muffle furnace at 450°C for 6 hours. LOI weight was used to calculate the %OM content as follows:

$$\% LOI = ((\text{Initial dry weight} - \text{Weight remaining after ignition}) / \text{Initial dry weight}) \times 100.$$

The sediment C<sub>org</sub> values were arrived at using one of the two equations depending on the organic matter content of the sediment sample:

$$\% LOI < 0.2 : \% C_{org} = 0.40 * \% LOI - 0.21$$

$$\% LOI > 0.2 : \% C_{org} = 0.43 * \% LOI - 0.33,$$

following recommended protocols for estimating carbon for the marine ecosystems [3,37]. Estimates for the top 50 cm of the sediment were extrapolated to one metre.

## Data analysis

Assumptions of normality and homogeneity of variance were tested by examining residuals in all relevant tests; where these were not met, data were transformed to meet parametric assumptions. One way ANOVAs were used to test for the differences in above-ground, below-ground and total biomass between species, with Tukey *post-hoc* analyses used to compare means when significant differences were detected. Linear regression analysis was used to determine possible relationships between above-and below-ground biomass and also between sediment  $C_{org}$  and the above-ground biomass for the species areas. Nested two-way ANOVAs were used to compare sediment  $C_{org}$  between each species and its un-vegetated control cores. In all statistical tests, the significance level was set at  $\alpha = 0.05$ .

## Results

### Sediment $C_{org}$ in seagrass areas and un-vegetated 'controls'

There was higher sediment  $C_{org}$  in the vegetated seagrass areas compared to the un-vegetated areas (Fig 2). Strikingly these differences persisted down to 50cm depth in all species; initial analyses using depth and 'treatment' (i.e. vegetated vs un-vegetated) as fixed factors in two way ANOVAs showed significant treatment effects but no depth or depth-treatment interaction effects. Hence fully nested ANOVAs, in which depth was nested within cores and treatment (vegetated/un-vegetated) to recognise non-independence of depth slices from the same cores, were subsequently used. These revealed highly significant effects of treatment on  $C_{org}$  density for each of the species:  $F_{(1, 180)} = 38.68, p < 0.001$  for *T. hemprichii*;  $F_{(1, 180)} = 27.89, p < 0.001$  for *T. ciliatum*;  $F_{(1, 180)} = 32.16; p < 0.001$  for *E. acoroides* and  $F_{(1, 180)} = 11.55, p = 0.003$  for *S. isoetifolium*.

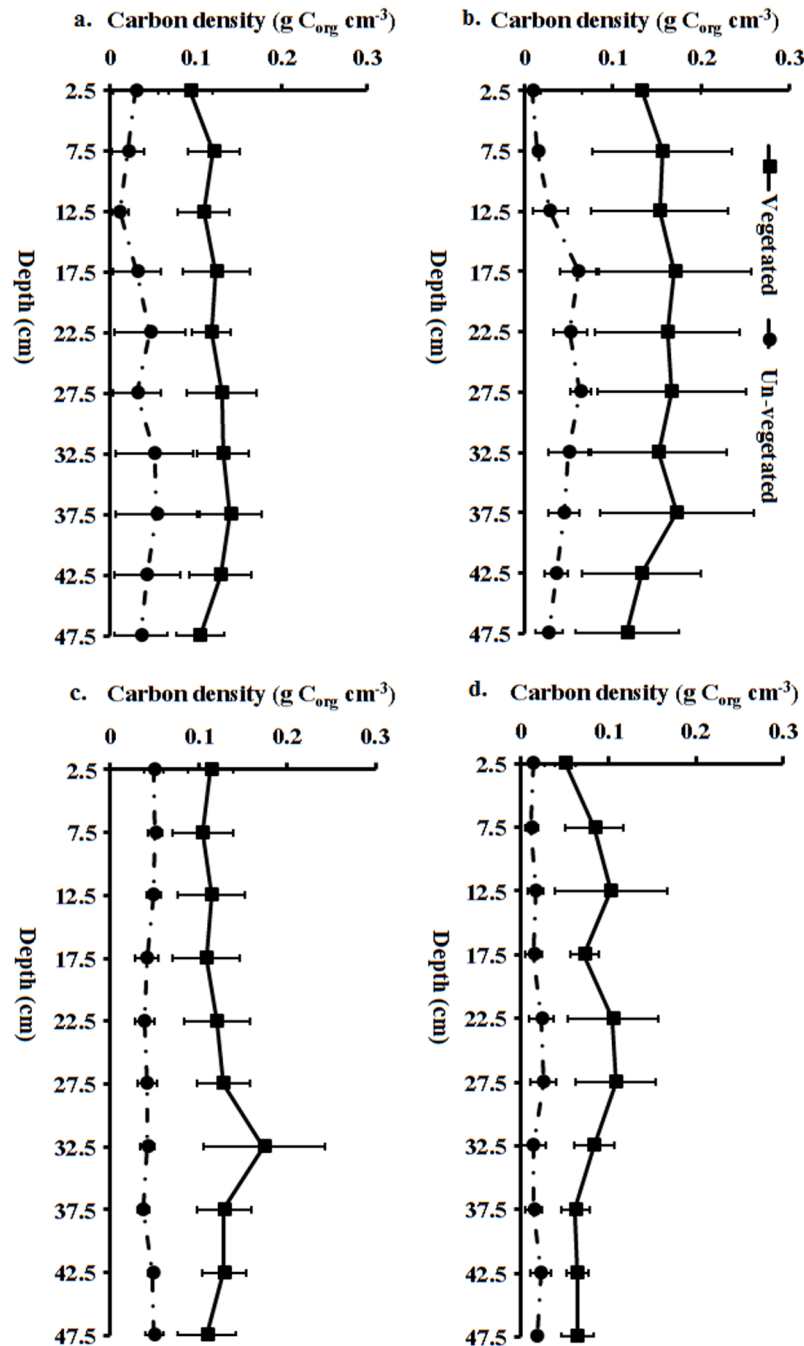
The sediment  $C_{org}$  varied between meadows of different species with the highest being recorded in *E. acoroides* at  $295.7 \pm 63.6$  (mean  $\pm$  95% C.I)  $Mg C ha^{-1}$  and the lowest in *S. isoetifolium* at  $160.7 \pm 40.3 Mg C ha^{-1}$  (Fig 3). A one way ANOVA showed significant differences in  $C_{org}$  among the species ( $F_{(3, 56)} = 6.24, p = 0.001$ ).

### Comparison of the sediment $C_{org}$ and the above-ground biomass $C_{org}$

The sediment  $C_{org}$  constituted the bulk of the total  $C_{org}$  in all four species areas (Fig 4). The sediment  $C_{org}$  of  $295.7 \pm 63.6 Mg C ha^{-1}$  (mean  $\pm$  95% C.I) for *T.ciliatum* accounted for the highest proportion at 98.1% of the total  $C_{org}$  per unit area dominated by the species while 95.8% was the lowest proportion recorded in *S. isoetifolium* areas. Plotting the sediment  $C_{org}$  against the above-ground biomass  $C_{org}$  for each of the four seagrass species showed no significant relationships.

### Relationships between above-and below-ground biomass

The highest mean AGB was associated with *T. ciliatum* while the lowest was associated with *E. acoroides* (Table 1). The highest mean BGB was recorded in the *S. isoetifolium* while the lowest was recorded in the *T. ciliatum*. Comparison of AGB and BGB relationships in the four species revealed a highly significant relationship in *E. acoroides*, ( $F_{(1, 38)} = 25.02, p < 0.001$ ) but there were no significant relationships between the BG and the AGB in the other species. BGB constituted the highest biomass component with an average of  $82.2 \pm 8\%$  (or  $\sim 4:1$  BG:AG biomass ratio) for all the species, with *E. acoroides* having the highest at  $90.9 \pm 1\%$  and *T. ciliatum* having the lowest at  $71.0 \pm 5\%$ .

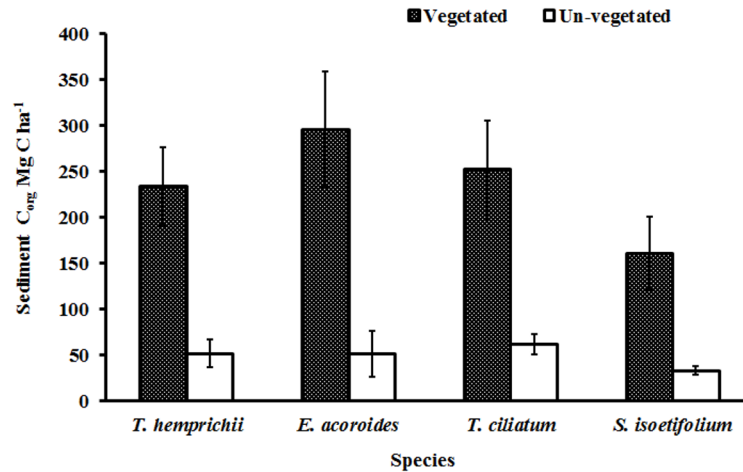


**Fig 2. Carbon density (mean  $\pm$  95% C.I.) along depth profiles in the vegetated and un-vegetated areas associated with the dominant seagrass species of Gazi Bay (a. *T. hemprichii* b. *E. acoroides* c. *T. ciliatum* d. *S. isoetifolium*).**

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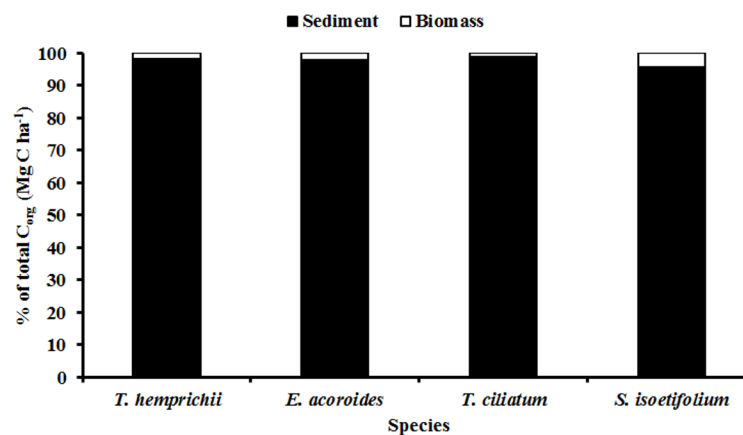
### Relationships between the total biomass and above-ground parameters

Total biomass varied between the species with the highest being recorded in *S. isoetifolium* at  $1985 \pm 246$  g DW m<sup>-2</sup> while *T. ciliatum* had the lowest at  $1405 \pm 233$  g DW m<sup>-2</sup>. The total biomass was significantly different between the species ( $F_{(3, 136)} = 4.13, p = 0.008$ ). No significant



**Fig 3. Variation in sediment C<sub>org</sub> between the vegetated and un-vegetated areas for the four seagrass species (means ± 95% C.I.).**

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**Fig 4. Relative % of the total C<sub>org</sub> (± 95% C.I) for the sediment and the biomass associated with the four dominant seagrass species at Gazi Bay.**

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relationships were found between the total biomass and shoot density for any of the species and neither between the total biomass and the shoot height, except in *T. ciliatum* ( $F_{(1,38)} = 9.83, p = 0.004$ ). The positive relationship between shoot density and % canopy cover was apparent across species (Table 1).

**Table 1. Mean (± 95% C.I) shoot density, canopy cover (%), canopy height (cm), above-ground (AGB), below-ground (BGB) and total biomass (TB) characteristics of the dominant seagrass species at Gazi Bay, Kenya.**

Species	Shoot density(m <sup>-2</sup> )	% C. cover	C. ht (cm)	AGB (g. DW m <sup>-2</sup> )	BGB g. DW m <sup>-2</sup> )	TB (g. DW m <sup>-2</sup> )	% BGB
<i>T. hemprichii</i>	996 ± 94	69.3 ± 4.2	18.4 ± 1.4	202.1 ± 29.9	1361.1 ± 281.8	1563.1 ± 279.2	82.8 ± 3
<i>E. acoroides</i>	248 ± 28	47.5 ± 4.2	55.1 ± 4.1	155.9 ± 23.7	1669.2 ± 217.6	1825.8 ± 234.8	90.9 ± 1
<i>T. ciliatum</i>	531 ± 67	61.9 ± 3.7	36.7 ± 3.9	308.2 ± 33.5	1096.6 ± 221.4	1404.9 ± 232.5	71.0 ± 5
<i>S. isoetifolium</i>	4351 ± 500	72.0 ± 7.0	23.3 ± 2.7	300.8 ± 42.6	1683.8 ± 242.9	1984.7 ± 245.5	84.0 ± 4

<https://doi.org/10.1371/journal.pone.0177001.t001>



## Discussion

The current study investigated biomass and sediment  $C_{\text{org}}$  stocks associated with the four dominant seagrass species of Gazi Bay, providing amongst the first data from Africa for seagrass sediment  $C_{\text{org}}$  [40]. It also compared sediment  $C_{\text{org}}$  in contiguous vegetated and un-vegetated areas for each of the species and demonstrated highly significant differences in carbon density, with the presence of seagrass enhancing sediment carbon stocks by a factor of 4–6, depending on the species. The mean sediment  $C_{\text{org}}$  estimated for the top one metre of the sediment (using IPCC protocols to extrapolate downwards from the 50cm measured depth) from seagrass vegetated areas was  $236 \pm 24 \text{ Mg C ha}^{-1}$ . This is well above the mean of  $166 \text{ Mg C ha}^{-1}$  derived from a global data set [3], (although within the range of  $115.5\text{--}829.2 \text{ Mg C ha}^{-1}$ ). Across all species, sediment depth did not have a significant effect on sediment  $C_{\text{org}}$  and the differences observed between vegetated and un-vegetated areas were consistent down to 50cm. This suggests a surprising degree of spatial consistency and longevity in these relatively small (typically 3 to 6m diameter) patches of seagrass meadow and bare areas. Sediment  $C_{\text{org}}$  dominated the carbon stocks in all species areas, constituting over 97% of the total  $C_{\text{org}}$  compared to less than 3% contributed by the biomass. Much of this sediment carbon is likely to be allochthonous; globally an average of ~50% of sediment  $C_{\text{org}}$  associated with seagrass meadows is derived from external sources [4]. In Gazi Bay much of this comes from mangroves; previous studies in Gazi Bay showed that mangrove carbon is exported to the seagrass beds where it is stripped from the water column and settles [25,41] with an estimated 21–71% of carbon exported from the fringing mangrove forests captured within the seagrass meadows [22].

Whilst there is a growing literature exploring sediment carbon in seagrass meadows there are few explicit comparisons of vegetated with un-vegetated areas. A limited number of studies have compared the sediment carbon stocks or both the stocks and burial rates in bare areas and naturally or artificially recolonized meadows [14,40–45]. For instance, a study on carbon accumulation in a restored seagrass meadow in Virginia, USA, in which sediment cores were taken to 10–20cm depth, [44] reported that after 9 years the meadow had 3 times more carbon than the un-vegetated areas, suggesting powerful effects of seagrass on C sequestration at this site and a rapid recovery in this service following restoration. A synthesis of global data [5] gave a mean sediment C burial rate of  $138 \text{ g C m}^{-2} \text{ yr}^{-1}$  in seagrass beds. A recent study in Oyster Harbour of Western Australia [40] reported that a restored seagrass meadow took 18 years to acquire a carbon accumulation rate of  $26.4 \pm 0.8 \text{ g C m}^{-2} \text{ yr}^{-1}$  and that a naturally vegetated area which was used as a reference had 63% and 37% more carbon than the un-vegetated and restored areas respectively. To our knowledge, the present study is the first one to compare sediment  $C_{\text{org}}$  for seagrass in naturally occurring vegetated and un-vegetated areas in Africa and it demonstrates an exceptionally powerful effect of seagrass on C sequestration, with relative C densities being higher in areas under seagrass compared with appropriate un-vegetated control areas and the differences being higher than in any other relevant studies.

A recent study using a global data set [46] reported an average sediment accretion rate of  $2 \text{ mm yr}^{-1}$  for seagrasses. If the sediment at Gazi accumulated at the same rate this suggests a minimum age of 250 years for sediment at 50cm, demonstrating that the current locations of seagrass meadow and bare patches are likely to have persisted for at least decades. However, a robust estimation method requires in-situ dating studies.

The present study did not establish any significant relationships between sediment and biomass  $C_{\text{org}}$  in any of the species. Lack of strong relationships between either the sediment  $C_{\text{org}}$  and the AGB or between the AGB and BGB measures means that AGB was not a suitable proxy for the determination of BGB or sediment  $C_{\text{org}}$  for any of these species and coring is therefore necessary for accurate estimates of these variables.

The biomass estimates obtained in the present study were within the range of published data for the same species in other parts of the world although tended towards the high end of these ranges [18,34,47]. The mean for the total biomass  $C_{org}$  for the four seagrass species was  $5.9 \pm 0.9 \text{ Mg C ha}^{-1}$ . As was the case for sediment  $C_{org}$ , this value is well above the global mean of  $2.51 \pm 0.49 \text{ Mg C ha}^{-1}$  (although *Posidonia oceanica* in the Mediterranean has greater biomass than our species, with a mean of  $7.29 \pm 1.52 \text{ Mg C ha}^{-1}$ ) [3]. Across all species, the BGB was much higher than the AGB, accounting for over 80% of the total. The fact that AGB in all species was substantially lower and slightly more variable than the BGB could be attributed to higher turnover rates for the AGB occasioned by grazing pressure, mechanical removal by tides and human activities such as seine fishing, events that were observed in the bay in the course of this study. Whilst larger species, such as *E. acoroides*, with large fronds and big roots and rhizomes, are likely to accumulate more biomass during growth which is invested in their below-ground tissues, shoot density is also an important parameter in determining per unit area BGB. *Syringodium isoetifolium*, which had a substantially higher shoot density and % canopy cover than the other species, recorded higher BGB than even the larger species.

Seagrasses cover an estimated area of  $7\text{km}^2$  within Gazi Bay [22], this is approximately 41% of the bay area considering the entire bay area of  $17\text{km}^2$ ). Extrapolation of the mean biomass and the sediment  $C_{org}$  values in the top one metre of the sediment gives an estimated total of 168,642 Mg C for seagrass meadow carbon stocks in the bay as a whole. If these findings are representative of seagrass meadows along much of the African coast the current absence of African sites from the global data will result in an underestimate of average carbon storage in seagrass meadows.

There are many sources of uncertainty in this estimate, however; for example we considered only the four dominant species, which constitute ~ 70% of the seagrasses of the bay, and other species areas may show different C densities. Future research at Gazi should not only aim to quantify the  $C_{org}$  from all seagrass species but should undertake a thorough mapping and estimation of the sedimentary  $C_{org}$  of the seagrasses of the entire bay for a better understanding of the carbon storage capacity of seagrasses there.

The present study has established that, as for other species and sites, the sediment  $C_{org}$  constitutes by far the major C pool for the seagrass beds of Gazi Bay. The highly significant differences in  $C_{org}$  between vegetated and un-vegetated areas underlines the importance of seagrass meadows as shallow marine C sinks, a service that adds to the many other justifications for their conservation. This study provides among the first estimates of sediment  $C_{org}$  from seagrasses in the Africa. As such it contributes to the growing global literature on the importance of seagrass meadows as C sinks. It also provides information of potential relevance to the conservation and management of seagrasses in the area. Gazi Bay hosts a pioneer carbon offset project “Mikoko Pamoja”, the first initiative in the world to restore and protect mangroves through the sale of carbon credits (<http://www.planvivo.org/project-network/mikoko-pamoja-kenya>). Knowledge of the carbon stocks associated with seagrasses in the bay may open opportunities for bundling seagrass ecosystem services with those of the mangrove ecosystem, an approach that makes ecological sense, given the strong connections between the two ecosystems.

## Supporting information

**S1 File. Carbon density (mean  $\pm$  95% C.I.) along depth profiles in the vegetated and un-vegetated areas associated with the dominant seagrass species of Gazi Bay (a. *T. hemprichii* b. *E. acoroides* c. *T. ciliatum* d. *S. isoetifolium*).**  
(XLSX)

**S2 File. Variation in sediment  $C_{org}$  between the vegetated and un-vegetated areas for the four seagrass species (means  $\pm$  95% C.I.).**

(XLSX)

**S3 File. Relative % of the total  $C_{org}$  ( $\pm$  95% C.I) for the sediment and the biomass associated with the four dominant seagrass species at Gazi Bay.**

(XLSX)

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