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Soil Carbon within the Mangrove Landscape in Rufiji River Delta, Tanzania

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Abstract

Mangroves are among the most carbon-rich terrestrial ecosystems, primarily attributable to the soil pool. There are substantial differences in soil carbon (C) and nitrogen (N) due to the disparities in geomorphic settings and ecological drivers, but this insight is drawn primarily from observational studies. An objective inventory of carbon stocks in mangroves of the Rufiji River Delta, Tanzania was conducted. Seventy-five soil cores were collected within a 12,164 ha inventory area, comprising the northern portion of the delta. Cores were collected from intact and dwarf mangroves, agricultural fields, and mudflats. The spatial mean soil organic carbon (SOC) density in mangroves was 16.35 ± 6.25 mg C cm^{-3}. Mean SOC density in non-vegetated mudflats was 12.16 ± 4.57 mg C cm^{-3}, demonstrating that mangroves develop on soils with a substantial soil C stock. However, long-established mangroves had had a higher C density (17.27 ± 5.87 mg C cm^{-3}). Using a δ^{13}C mixing model, the source of soil organic matter in mudflats was primarily marine, while long-established mangroves was predominantly mangrove. There were small differences in SOC among long-established mangrove sites in different geomorphic settings. The proportion of marine-sourced SOC increased with soil depth in mangroves. The SOC and nitrogen of agricultural sites resemble those of mudflats, suggesting those sites are developed from relatively young forests. The SOC and nitrogen density in dwarf mangrove sites were lower than others, perhaps reflecting past disturbances.

Keywords Blue carbon · Soil nitrogen · δ^{13}C · δ^{15}N · Carbon stock inventory · Forested wetland

Introduction

Mangroves are dynamic and important ecosystems of tropical coasts (Lugo and Snedaker 1974; Eong 1993), providing a variety of valued ecosystem services (Bosire et al. 2008; Nagelkerken et al. 2008). The foundation of many of the ecosystem functions is the ecosystem carbon stock that is higher than terrestrial forests (Donato et al. 2011), and the soil is the principal determinant of the large ecosystem carbon stock (Matsui 1998; Donato et al. 2011; Kauffman et al. 2011, 2014; Wang et al. 2013; Jones et al. 2014). However, there are substantial differences in soil organic carbon (SOC) density[1] among global mangroves, ranging from 0.32 to 133.81 mg C cm^{-3} with an arithmetic mean of 30.87 mg C cm^{-3}, geometric mean of 25.27 mg C cm^{-3} and median of 28.29 mg cm^{-3}, based on the dataset of global mangrove soils compiled by Sanderman (2017) and summarized by Sanderman et al. (2018); approximately 44% of published reports indicate less than 25 mg C cm^{-3}, and about 50% of reports show SOC between 20 and 50 mg C cm^{-3}, reflecting that the global distribution of SOC density in mangrove soils is skewed. Accordingly, the wide variation in the soil C pool in mangroves suggests the merit for additional measurements to better facilitate the role of mangroves to the global terrestrial C stock.

The dynamics of carbon (C) and nitrogen (N) in mangrove soils are different from those in freshwater forested

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[1] Density of soil C and N (mg cm^{-3}) is used in this study, similar to the concentration suggested by Tolhurst et al. (2005).

terrestrial wetlands because of tide and marine influences. Accordingly, C and N geochemistry in mangrove soils, including elemental and isotopic geochemistry, may reflect the responses of mangroves to sea level rise (Khan et al. 2015), storms and tsunamis (Kathiresan and Rajendran 2005; Alongi 2008; Gilman et al. 2008; Kauffman and Cole 2010) and differences in ecological drivers (Middelburg and Herman 2007; Krauss et al. 2008; Livesley and Andrusiak 2012), which are useful to understand the role of mangroves in changing environment and climate. The information from the combining their elemental components and isotopic signatures may be used to assess the source and fate of organic matter (OM) in mangrove ecosystems and estuarine sediments (Andrews et al. 1998; Graham et al. 2001).

Most of the information on SOC concentration/content in mangroves is derived from observational studies. Our purpose in this study is to objectively characterize the spatial distribution of SOC in a large tract of mangroves, and to determine whether the presence of mangroves affects the SOC by comparing soil C pools among different land uses within a common landscape. Accordingly, we assess the spatial distributions of soil C and N stocks, and utilize soil $\delta^{13}C$ and $\delta^{15}N$ signatures to assess the contributions of mangroves to the soil C pool as well as considering effects of geographic setting and climate on the development of soil C stocks within Rufiji Delta.

Methods and Materials

Study Site

This site is located in Rufiji River Delta of Tanzania (7.760–7.858°S and 39.215–39.405°E). The Rufiji River is one of the largest river systems in East Africa, with an approximate length of 600 km and a catchment area of 177,000 km^2 (Arvidson et al. 2009). The river basin drains about 20% of Tanzania and is commonly divided into four geographical sections: the Great Ruaha, the Kilombero, the Luwegu and the lower Rufiji. The lower section contains the Rufiji Delta at the mouth to the Indian Ocean where extensive mangroves are supported (Fig. 1).

The geomorphology of the Rufiji Delta is heavily affected by upstream activities and water flows. Additionally, the delta is subject to frequent storms that can cause geomorphic changes and also damage tree stands. The water level and hydroperiod in the Rufiji Delta are reflective of the cumulative runoff patterns in the upstream sub-basins (Francis 1992) and tidal influences. The tidal regime in the delta is semi-diurnal, with a mean of tidal range of 3.3 m (Ellison 2012), reaching about 25 km upstream (Mwalyosi 1991). The delta, its surrounding floodplain, and near shore habitats form a seascape consisting of a variety of interacting coastal and marine ecosystems that support diverse resources, upon which the

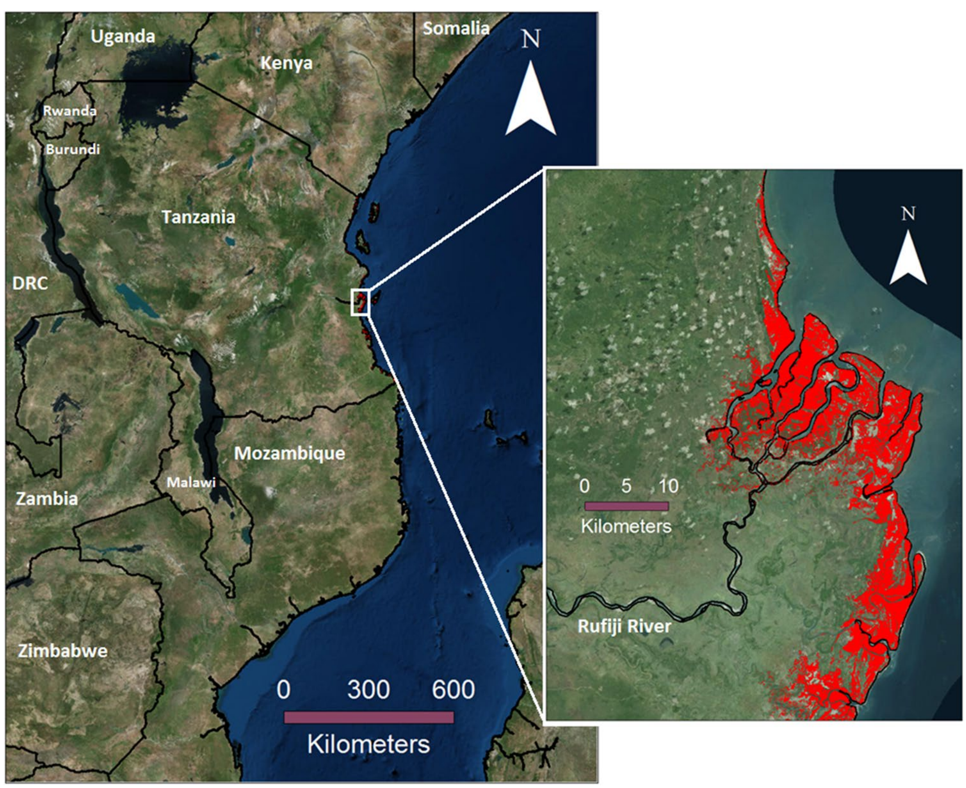

Fig. 1 Rufiji River Delta in Tanzania; the red area indicates the extent of mangroves based on the dataset from Giri et al. (2011a, b). The inventory area (12,164 ha) is indicated in the northern portion of the delta

traditional communities in the area have depended for centuries (Semesi 1991).

The climate of coastal Tanzania is tropical, with two distinct seasons, the rainy and dry seasons. There are two distinct rainy seasons in the vicinity of the Rufiji Delta, the “short rains” occur from October to December, and the “long rains” from February to May with peak rainfall in March. Most of the rain falls during long rains (Temple and Sundborg 1972). The mean annual precipitation ranges from 1,000 mm at the most upstream regions of the delta to more than 1,400 mm along the coast, with considerable inter-annual variation. The Rufiji Delta is vulnerable to tropical storm activity (Ellison 2012). Cyclones cause torrential rains that can occur during inter-monsoonal rains in November–December and March–May, regularly causing widespread local flooding (Bantje 1979; Semesi 1991; Duvail and Hamerlynck 2007). Mean monthly minimum temperatures at the delta along the coast ranges from 21.0 °C in July to 24.9 °C in February, the mean maximum temperature from 28.1 °C in July to 31.7 °C in February, annual mean air temperature is 26.6 °C in a 30-year period from 1970 to 2000, based on the world climate data (Hijmans et al. 2005).

The distribution and composition of mangroves are dynamic and directly related to geomorphological changes occurring as a function of coastal erosion and sedimentation processes (Smith 1992; Moll and Werger 1978) as well as harvesting and conversion of mangroves to agricultural use. Mangroves in Rufiji Delta are divided in three blocks: the northern block constitutes to over half of the total area of mangroves, the central block has the smallest and relatively sparse mangrove area, and southern block has about half the mangrove north. Eight of the 10 mangrove species occurring in Tanzania are found in the Rufiji Delta. *Rhizophora mucronata*, *Ceriops tagal*, *Bruguiera gymnorrhiza, Xylocarpus granatum*, *Avicennia marina*, *Sonneratia alba*, and *Heritiera littoralis*, are common and occur both in patches of pure and mixed stands. *Lumnitzera racemosa* is limited, *Xylocarpus moluccensis* and *Pemphis acidula* have not been reported from the delta (Taylor et al. 2003; FAO 2007). Mangrove associate species tend to occur in higher elevation areas with less water inundation (Vilankulos and Marquez 2000). Major associates include *Guettarda speciosa*, *Hibiscus tiliaceous*, and the large fern *Achrostichum aureum*. Thickets or patches of *Derris trifoliata*, a climbing liana, are common along most upstream reaches of tidal influence within the delta; this vine can over-top mangroves and develop very dense stands, widely common in successive vegetation following degradation from cutting and conversion.

Sampling Design

This sampling design was developed to objectively assess C stocks in mangroves within Rufiji Delta. We used a stratified random sampling design because it can add efficiency and accuracy to the assessment if the strata have a functional relationship with the variable(s) being measured. We used forest canopy height as the basis for stratification, developing seven canopy height classes for sampling (Table 1).

In addition to the consideration of tree canopy height, four hydrogeomorphic settings were noted, seaward (SW), riverine (RV), creek (CK) and interior (IT). The plots classified into SW were near the Indian Ocean and within the mouth of Rufiji River, plots categorized into RV were along main channels and within a distance of ≤ 50 m to the nearest channel, those grouped into CK near (≤ 50 m) a small branch, and those categorized into IT were far (> 50 m) from a main channel or branch.

A Spatial Decision Support System (SDSS) developed by Tang et al. (2016) was used to allocate sampling plots within strata based on the categories of the tree canopy heights and hydrogeomorphic settings while considering logistical, operational and safety constraints. Forty-nine plots (0.0414 ha) were randomly located within the strata to collect vegetation measurements and soil samples within the inventory area. To compare mangrove soil C stocks with other land cove condition, random cores were also collected from land converted to agriculture (AG), un-vegetated emergent mudflats (MN), mudflats with recently established mangroves in the vicinity of MN (MM), and sparsely populated dwarf mangrove areas (DF).

Sample Collection

The soils were sampled to a depth of 200 cm (Trettin et al. 2020). Three cores were randomly collected from within each plot, using a 1 m gouge auger (AMS Inc., American Falls, Idaho, USA). Samples were collected to represent 6 sampling depth intervals (Table 2). At each sampling depth interval, a 5 cm section of the core was cut and extracted; the samples from the three cores were composited in the field. The soil cores for dwarf mangroves, agricultural lands and mudflats were sampled to a depth of 100 cm with five depth intervals (Table 2). The sample depth interval was adjusted

Table 1 Mangrove soil groups based on tree heights

Tree height class	Height range (m)	Group name
0	< 1	H0
1	1 – 4.9	H1
2	5 – 9.9	H2
3	10 – 14.9	H3
4	15 – 19.9	H4
5	20 – 24.9	H5
6	25 – 36+	H6

Table 2 Soil layers represented by samples and the sampling depth intervals for each soil core

Sample location	Interval	Soil layer (cm below surface)	Depth interval (cm below surface)	Mean depth (cm)
Mangrove forest cover	1	0–15	5–10	7.5
	2	15–30	20–25	22.5
	3	30–45	35–40	37.5
	4	45–110	70–75	72.5
	5	110–185	145–150	147.5
	6	185–200	190–195	192.5
Other land cover	1	0–15	5–10	7.5
	2	15–30	20–25	22.5
	3	30–45	35–40	37.5
	4	45–60	50–55	52.5
	5	60–100	85–90	87.5

within the layer if the designated zone was disturbed to ensure accurate volumetric sample.

Sample Processing and Analysis

Soil samples were placed in a 105 °C oven and dried until a constant weight was achieved for the determination of the oven-dried weight of the volumetric sample. The bulk density (g cm^{-3}) of each sample was calculated by dividing the oven-dried mass by the composite sample volume. After drying, samples were ground and coarse roots (> 2 mm) removed. A subset of samples (n = 60) was from four sampling depth intervals of 15 cores, which represented the soils from different geomorphic settings, including samples from different tree canopy heights and those distinct geomorphic settings related to hydrology in the Rufiji Delta. These subsamples were used to test for the presence of carbonates following procedures detailed by Thomas (1996); none were positive.

The SOC and total N (TN) concentrations were determined by the University of Georgia Analytical Laboratory using a Perkin Elmer 2400 Series II CHNS/O Analyzer (Perkin Elmer, Waltham, MA, USA).[2] Instrument settings and procedures followed the recommended application protocols described by Perkin Elmer (2010). Quality assurance of analyses was provided by the analysis of duplicates, and calibration of the instrument with certified standards. The precision of duplicate samples was ± 0.1% for C and 0.02% for N or better, respectively. The δ^{13}C and δ^{15}N values of soil samples were determined using a Thermo Delta V stable isotope ratio mass spectrometer (Thermo Fisher Scientific Inc., Bremen, Germany). The isotopic signatures were reported using common delta notation (δ). The duplicate sample standard deviations for δ^{13}C and δ^{15}N were ± 0.2‰ and 0.6‰ or lower, respectively.

A subset of the mangrove plots ($n = 15$) was used to characterize the particle size of the soils to a depth of 100 cm. The selection of these plots was identical to those selected to test carbonates in the soils, which represented the soils from different geomorphic settings. The particle size ranges were < 2 µm (clay), 2 – 50 µm (silt) and 50 µm – < 2 mm (sand). The analysis was conducted by Environmental Soil Analysis Laboratory in University of Nevada Las Vegas using a Malvern Master 2000 laser particle size analyzer equipped with a Hydro S dispersant unit (Marlvern Instruments Ltd., Malvern, UK). The particle size distribution data were automatically generated using the Mie Theory by the software associated with the instrument, with material refractive index of 1.544 and absorption index 1.0 as recommended by Ryzak and Bieganowski (2011). Each measured value was averaged from three replicates.

Statistics and Data Processing

Univariate regression analysis was used to assess the spatial distribution of SOC, TN, isotopic signature (δ^{13}C and δ^{15}N) in soils and the relationship between them. The radio of C to N is the molar ratio, i.e.,

$$Rt = \frac{C\_molarity}{N\_molarity} \tag{1}$$

where *Rt* is the C/N molar ratio, *C_molarity* and *N_molarity* are the masses of C and N divided by their atomic mass (C atomic mass: 12.0107; N atomic mass: 14.0067).

The proportion of SOC in mangrove derived from marine and terrestrial sources can be estimated with a two-source mixing model (Kristensen et al. 2008). Accordingly, the proportion of SOC attributable to those sources was calculated using the mixing model suggested by Ranjan et al. (2011):

[2] Analyses conducted at the University of Georgia, Odum School of Ecology Analytical Laboratory, Athens, Georgia, U.S.A.

$$F_{mar} = \frac{\delta^{13}C_{terr} - \delta^{13}C_s}{\delta^{13}C_{terr} - \delta^{13}C_{mar}} \tag{2}$$

and

$$F_{terr} = 1.0 - F_{mar} \tag{3}$$

where F_{mar} is the mixing ratio or fraction of marine C; $\delta^{13}C_{terr} = -28$ ‰ and $\delta^{13}C_{mar} = -18$ ‰ are the means of terrestrial and marine sources, respectively; $\delta^{13}C_s$ is the measurement from samples; F_{terr} is the mixing ratio or fraction of terrestrial C, which includes mangrove and other forest plant litter and SOC brought from inland surface and subsurface flows.

Overall mean for mangrove soils was averaged from all samples from 47 mangrove plots and the spatial mean for each sampling depth interval was from all samples at same interval, calculated, respectively, as

$$M_o = \frac{1}{k}\sum_1^k\left(\frac{1}{j}\sum_1^j O_{jk}\right) \tag{4}$$

$$M_j = \frac{1}{k}\sum_1^k O_{jk} \tag{5}$$

where M_o is the overall mean that is averaged from all observed samples; M_j is the spatial mean for the j^{th} sampling depth interval averaged from all samples at the same sampling depth interval; and k is the number of observed plots, j is the number of sampling depth intervals. Additionally, we assumed that the observed value of C, N, $\delta^{13}C$ and $\delta^{15}N$ from a sampling depth interval represented the value at the point of the mean sampling depth for the interval (see Table 1).

Results

Bulk Density and Texture of Mangrove Soils

The overall mean bulk density of the mangrove soils was 0.83 g cm^{-3}. The vertical distribution of mean soil bulk density varied with soil depth, ranging from 0.73 g cm^{-3} at 0–15 cm to 0.94 g cm^{-3} at 185 – 200 cm (Fig. 2A), increasing linearly with soil depth ($R^2 = 0.9574$, n = 6, $P < 0.001$), i.e.,

$$BD = 0.0011 \times D + 0.7422 \tag{6}$$

where BD is soil bulk density (g cm^{-3}); D is soil depth from the surface (cm). There is only a small difference (t = -1.90, i.e., $|t|$ = 1.90 > 1.734) in mean soil bulk density between H2 (0.69 g cm^{-3}) and H4 (0.89 g cm^{-3}), no substantial differences among the other canopy height classes ($P \geq 0.05$) (Fig. 2B).

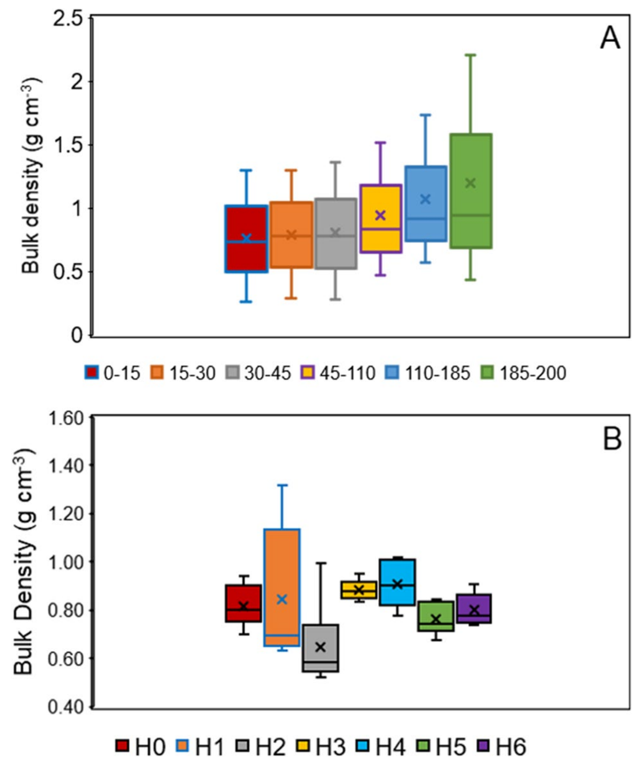

Fig. 2 Mean soil bulk density including median at different soil sampling depth intervals (**A**), and bulk density grouped by the tree canopy heights (**B**); bars: the standard deviations of bulk density; crosses: the means

The soil texture was dominated by silt; the average content of clay, silt and sand were 16.5 ± 3.9, 67.7 ± 10.2 and 15.8 ± 13.1%, respectively. There were small insignificant differences in the soil texture among the sampling strata with H0 plots tending to have less sand and more silt (Fig. 3). Similarly, when the plots were grouped by hydrogeomorphic setting, there was little difference with

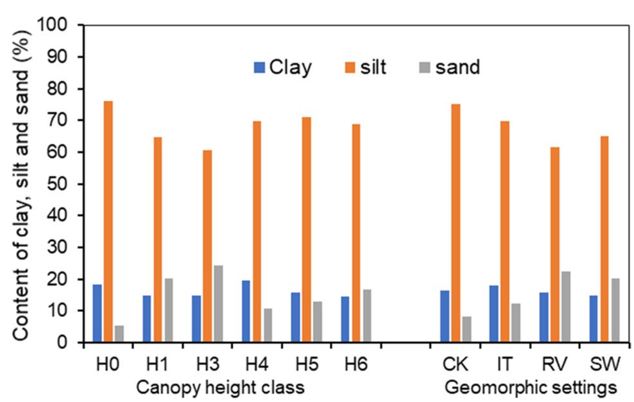

Fig. 3 Soil textural components within the sample strata (H0 – H6), soils grouped by hydrogeomorphic setting: Creek (CK), Interior (IT), Seaward (SW), and Riverine (RV)

riverine and seaward plots tending to have more sand and less silt (Fig. 3).

Soil Carbon and Nitrogen in Mangroves

SOC density in mangrove soils varied from 1.86 to 46.21 mg C cm^{-3} with an overall mean of 16.35 mg C cm^{-3}, which yields a spatial mean C pool of 316.9 Mg C ha^{-1} to 200 cm depth. The vertical variation in spatial mean SOC was small and nonlinear – quadratic with sampling depth ($R^2 = 0.81$, $n = 6$, $P < 0.02$; Fig. 4A); the SOC density among sampling depth intervals increased slightly from 16.25 mg C cm^{-3} at the interval 1 to 17.90 mg C cm^{-3} at the interval 4, and then decreased from 17.90 mg C cm^{-3} at the interval 4 to 14.92 mg C cm^{-3} at the interval 6. The vertical variation of SOC was also different among the canopy height classes (Fig. 4B). The SOC varied little for H0 with an increase in soil depth (Fig. 4B), although SOC at the interval 6 (8.90 mg C cm^{-3}) was lower than that at the intervals 1 – 5 (10.13 mg C cm^{-3} at the interval 2 to 11.07 mg C cm^{-3} at the interval 4). However, the vertical changes in the SOC for other groups were non-linear. The differences in SOC among the sampling strata for most height classes were small, except for H2 in which SOC at the stratum 4 was substantially higher than the strata 1 – 3 and 6 ($P < 0.05$). There was a trend in the averaged SOC increased from H0 to H3 and then decreased small from H3 to H6. Accordingly, the variation of SOC among the height classes was quadratic ($R^2 = 0.83$, n = 6, $P < 0.001$).

There were small differences in SOC among mangrove soils grouped by geomorphic settings (Fig. 4C). The Interior (IT) contained slightly more organic C than that of other groups, and the seaward (SW) was slightly less than that of other groups. There were some small differences in SOC among the sampling strata and geomorphic settings. SOC at the interval 1 in Creek (CK) and Riverine (RV) was higher than that at the intervals 2 and 3 (Fig. 4C). However, the vertical variation of SOC in Seaward (SW) and IT was opposite, SOC in the soil layer of IT and SW from the surface to 75 cm in depth increased with an increase in soil depth, and then decreased with soil depth, thus, the vertical distribution of SOC in IT and SW was quadratic. However, the vertical distribution of SOC in CK and RV was an S shape.

Soil TN varied, ranging from 0.14 to 1.90 mg N cm^{-3} with an overall mean density of 0.91 ± 0.24 mg N cm^{-3} and total average N pool of 11.5 Mg N ha^{-1} to 200 cm in depth. The vertical variation of soil TN in the delta decreased quadratically with an increase in soil depth from the surface ($R^2 = 0.98$, n = 6, $P < 0.01$; Fig. 5A), decreasing from 1.06 mg N cm^{-3} at the interval 1to 0.75 mg N cm^{-3} at the interval 6. There were small differences in TN among the mangrove soils grouped by canopy height (Fig. 5B), the mean TN for these groups from H0 to H6 was 0.765, 0.674, 0.814, 0.981, 0.904, 1.021, and 0.894, respectively.

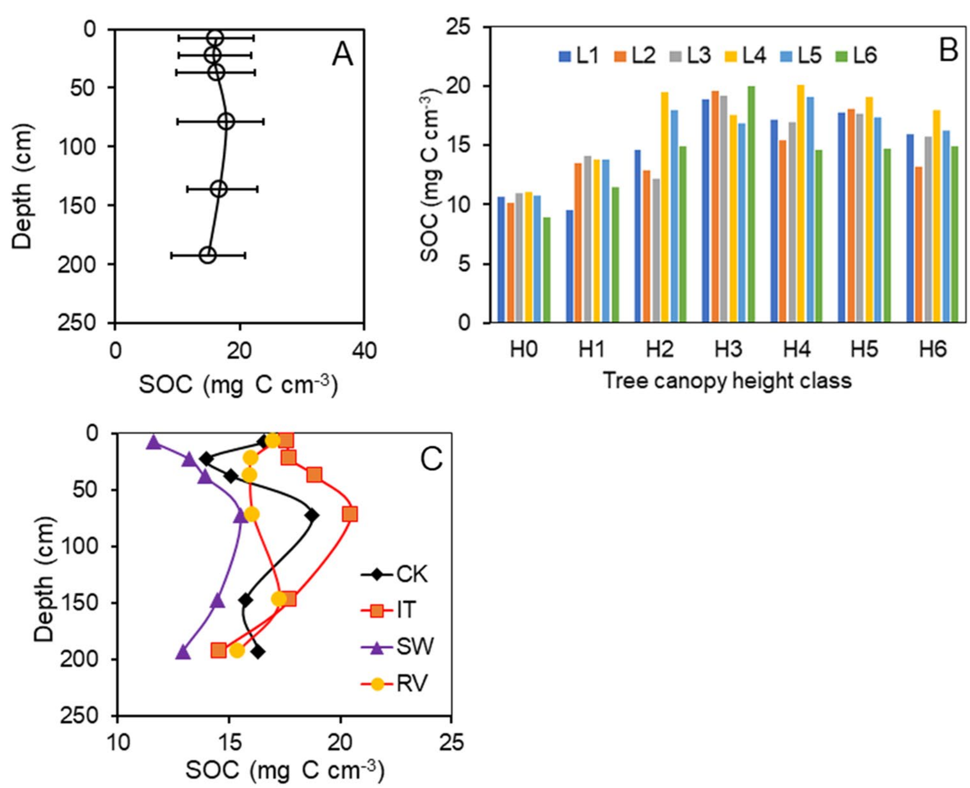

Fig. 4 Mean SOC (mg C cm^{-3}) at different soil depths for mangrove soils (**A**), bars represent the standard deviation (±1 SD); means at different tree canopy height (**B**), sampling depth, L1: 0 – 15 cm, L2: 15 – 30 cm, L3: 30 – 45 cm, L4: 45 – 110 cm, L5: 110 – 185, L6: 185 – 200 cm; means in different hydrogeomorphic settings (**C**); CK: Creek; IT: Interior; RV: Riverine; SW: Seaward

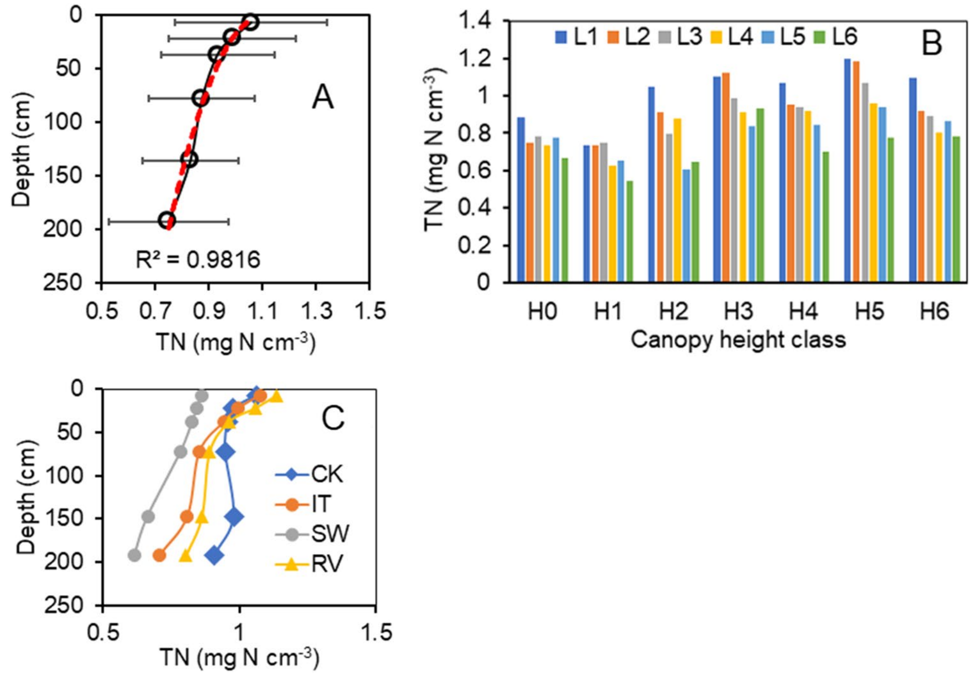

Fig. 5 Mean soil TN (mg N cm^{-3}) for different depth in the Rufiji Delta (**A**), vertical variation with standard deviation (± 1 SD) at mangrove landscape level; means in the mangrove soils grouped by tree canopy heights (**B**), L1 – L6 are the six sampling strata, L1: 0 – 15 cm, L2: 15 – 30 cm, L3: 30 – 45 cm, L4: 45 – 110 cm, L5: 110 – 185 cm, and L6: 185 – 200 cm; means in different mangrove soils grouped by geomorphic settings(**C**); CK: Creek; IT: Interior; RV: Riverine; SW: Seaward

There were statistically insignificant differences in mean TN soil density among the mangrove soils grouped by geomorphic settings, about 0.972, 0.898, and 0.953 mg N cm^{-3} for CK, IT, and RV, respectively, but TN in SW (0.766 mg N cm^{-3}) was slightly lower than other settings. TN in the top layer (0 – 15 cm in depth) for these four settings was higher than that in other layers (Fig. 5C). However, there were differences in vertical variation of TN among the groups. TN decreased S-shapely with an increase in soil depth in the setting CK. However, TN decreased linearly with an increase in soil depth in SW ($P < 0.01$), and quadratically in IT and RV.

Overall the C/N ratio varied from 9.6 to 40.2 with a mean of 18.1 in the mangrove soils in Rufiji Delta. The spatial mean ratio for the sampling depth intervals was the smallest (17.8) at the interval 1, and the largest (23.7) at the interval 4; it significantly increased nonlinearly (cubic polynomial) with an increase in the soil depth from the sampling depth interval 1 (Fig. 6A; $R^2 = 0.9569$, $n = 6$, $P < 0.001$). The mean C/N ratios for mangrove soils among the four geomorphic settings differ small (Fig. 6B), about 18.8, 22.6, 20.1 and 21.2 for the groups CK, IT, RV, and SW, respectively.

Soil Carbon and Nitrogen in Other Land Cover Classes

The mean SOC in AG, DF, MM and MN was 12.4, 9.7, 12.0, and 13.3 mg C cm^{-3}, showing that there were small and statistically insignificant ($\mu 1 = \mu 2$, $P \leq 0.05$) differences in SOC among AG, MM and MN cover classes (Fig. 7A), but DF was significantly less than the other classes ($P < 0.01$). The SOC in MN was slightly higher than that in others, especially higher than the SOC measured in DF. The vertical distribution in SOC among these four land cover types

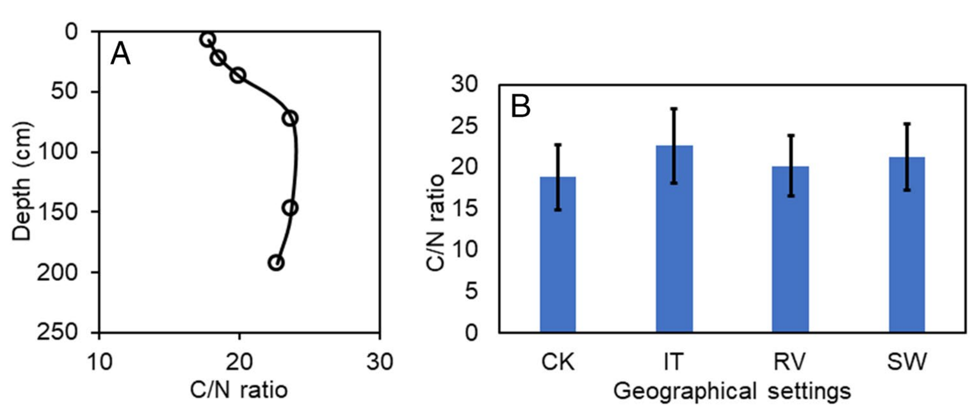

Fig. 6 Changes in mangrove soil C/N ratio with depth from the surface (**A**), the soil C/N ratio for soils grouped by geomorphic settings (**B**); CK: Creek; IT: Interior; RV: Riverine; SW: Seaward; bar is standard deviation (± 1 SD)

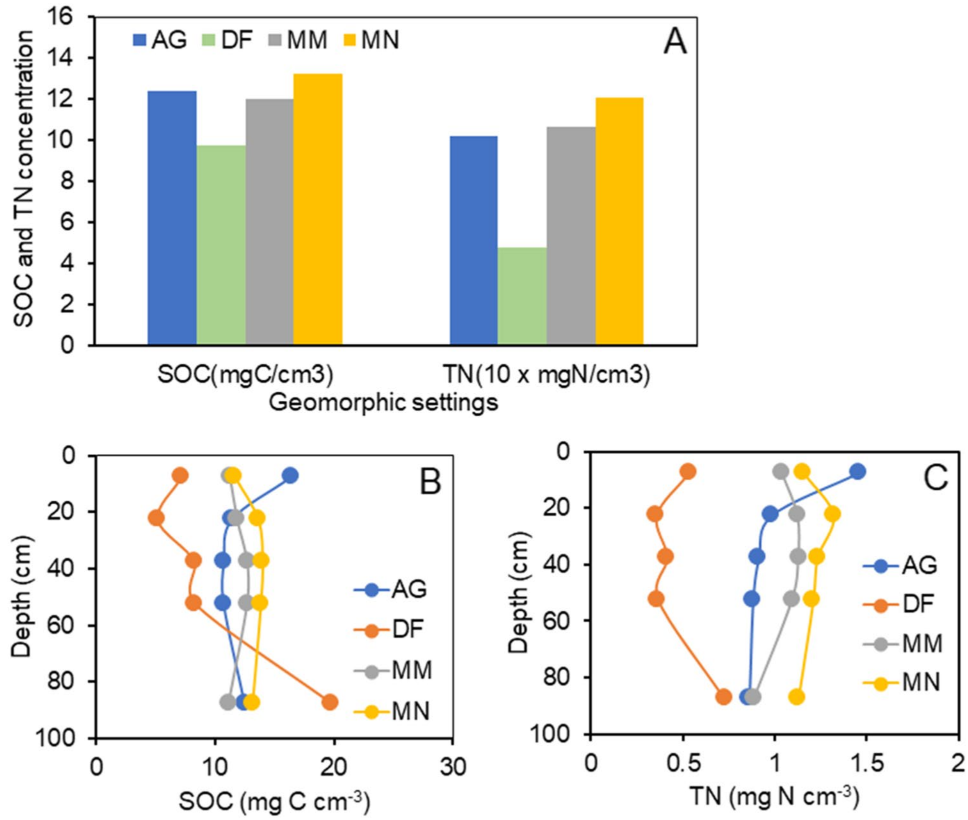

Fig. 7 Overall means of SOC (mg C cm^{-3}) and TN in non-mangrove soils grouped by land types (**A**), the TN value in panel A is magnified by a factor of 10, the true value should be the value in panel A divided by 10, after that the unit is mg N cm^{-3}; AG: agriculture land; DF: dwarf mangrove with very sparse stands; MM: mudflat with recently established mangroves; MN: un-vegetated emergent mudflat; vertical variation in SOC (**B**) and TN (**C**) in non-mangrove soils

varied (Fig. 7B). The SOC in MM and MN decreased insignificantly below 20 cm. However, the vertical variation in SOC in DF was quadratic, and the variation in AG followed a power function. The SOC at the interval 1 (0 – 15 cm) in AG was the highest, then decreased from 16.4 mg C cm^{-3} at the interval 1 to 11.4 mg C cm^{-3} at the interval 2 followed by small changes with depth. The vertical change trend in SOC in DF showed a different pattern, with an increase in soil depth, increased from a density of 7.1 mg C cm^{-3} at the interval 0 – 15 cm to a density of 19.7 mg C cm^{-3} at the interval 60 – 100 cm, which is higher than or similar to the overall mean (17.9 mg C cm^{-3}) of the intact mangrove soils at the similar soil depth in the delta.

Soil total nitrogen density in DF was less than a half of the TN in other settings (Fig. 7A). The pattern of the vertical alteration of the TN in these land cover classes was similar to the distributions of SOC (Fig. 7B), with the TN density in MM and MN decreasing insignificantly with an increase in soil depth (Fig. 7C). The vertical variation in AG followed a power function ($P < 0.02$), and was quadratic in DF ($P < 0.01$), and TN density at the interval 5 (60 – 100 cm in depth) of DF was higher than other soil layers within the same cover class. Comparing with other cover classes, TN at intervals 1–4 in DF was lower than at the same level in AG, MM and MN, the ratios of each of intervals 1–4 to interval 5 were 0.68, 0.50, 0.52 and 0.47, respectively.

Isotopic Signatures in the Mangrove soils

The soil δ^{13}C decreased linearly with an increase in SOC ($P < 0.001$; Fig. 8A). Within the solum soil δ^{13}C increased nonlinearly with an increase in soil depth (Fig. 8B; $R^2 = 0.966$, $n = 6$, $P < 0.01$) although the lowest mean value occurred between 45 – 100 cm.

$$\delta^{13}C(\%_0) = 0.3331 \times D^2 - 0.1693 \times D - 24.172 \qquad (7)$$

where D is the soil depth (m) from the surface.

There were differences in vertical distribution of δ^{13}C values among the mangrove soils grouped by hydrogeomorphic setting (Fig. 8C). That vertical distribution pattern could be divided into two groups: CK & RV, and IT & SW. The soil δ^{13}C value in the CK interval 2 was the highest, and there was no statistical difference in the soil δ^{13}C signature among the other intervals within this soil group, excepting interval 2. The differences in the δ^{13}C values among the sampling depth intervals in RV were small and insignificant. Accordingly, there was no statistical trend in the δ^{13}C with variations in soil depth in CK and RV. The IT & SW group tended to be lower than the other group; however, the values at below 115 cm were substantially higher than in the overlaying soil for those classes. The overall trend was an increasing with sampling depth for IT & SW.

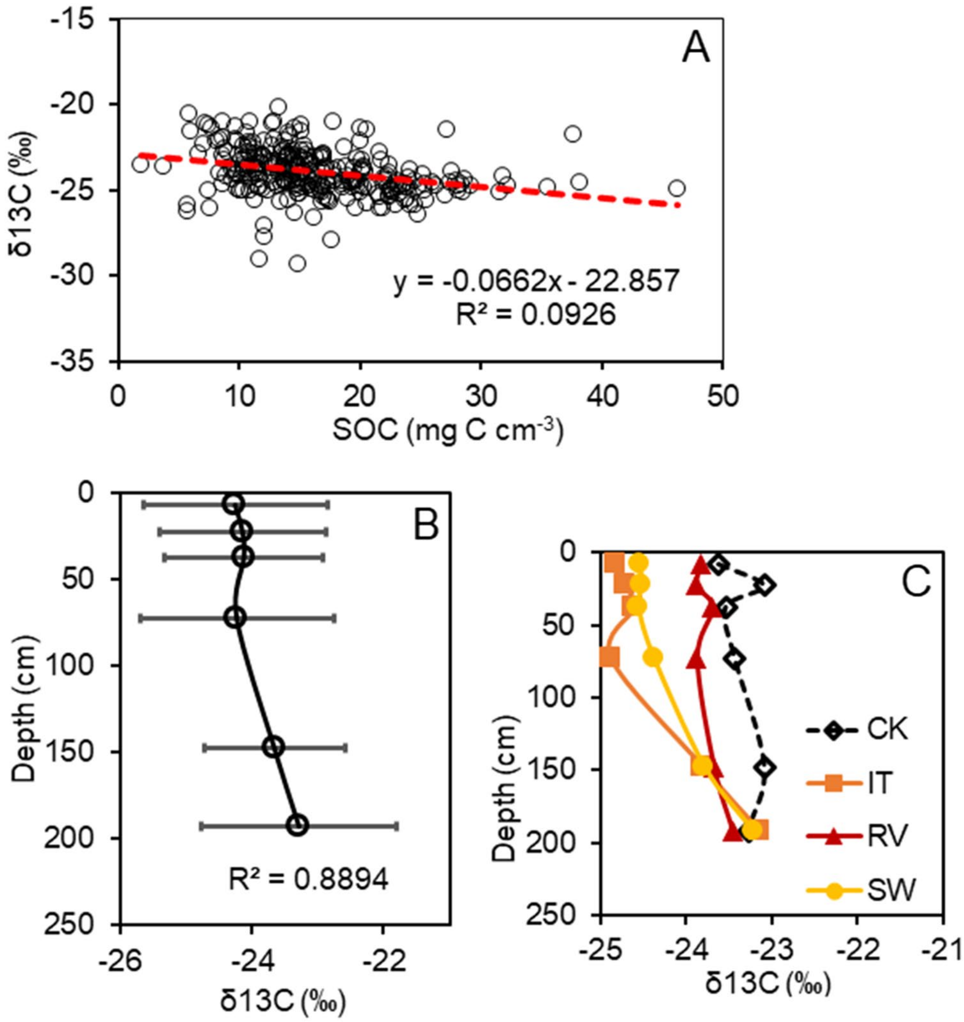

Fig. 8 Mean SOC density vs. $\delta^{13}C$ (‰) for samples within 0–200 cm depth (**A**), vertical variation of mean $\delta^{13}C$ with soil depth (**B**), and changes in mean $\delta^{13}C$ with soil depth in the mangrove soils grouped by geomorphic settings (CK: Creek; IT: Interior; RV: Riverine; SW: Seaward) (**C**), in Rufiji Delta in Tanzania

The vertical change of $\delta^{15}N$ values with increasing soil depth in the mangrove soils in Rufiji Delta was different from that of $\delta^{13}C$. The $\delta^{15}N$ decreased with an increment in soil depth between 0 – 115 cm, and then it increased with an increase in the soil depth between intervals 4 and 6, thus, the $\delta^{15}N$ values substantially varied nonlinearly with soil depth (Fig. 9A; $R^2 = 0.9598$, $n = 6$, $P < 0.001$), following a cubic polynomial:

$$\delta^{15}N(\%_0) = -0.3381 \times D^3 + 1.7001 \times D^2 - 2.0806 \times D + 3.5114 \quad (8)$$

where D is the soil depth (m) from the surface. The vertical alteration of $\delta^{15}N$ in the mangrove soils grouped by geomorphic settings was nonlinear too (Fig. 9B), but their changing patterns were not the same among the settings, quadratic for settings IT ($P < 0.001$) and SW ($P < 0.02$), but quartic polynomial for CK ($P < 0.001$) and RV ($P < 0.001$).

There were differences in the mean ratios of $\delta^{13}C$ to $\delta^{15}N$ at different soil depths (Fig. 10A), the largest ratio (-7.7) occurred in the deep subsoil and the smallest value (-16.8) at 30 – 45 cm. The mean ratio of $\delta^{13}C$ to $\delta^{15}N$ in the mangrove soils in the 0 – 30 cm depth was proximate to that in the 185 – 200 cm depth.

The spatial mean ratio of $\delta^{13}C$ to $\delta^{15}N$ in the soils below 30 cm in depth from the surface significantly increased with an increase in soil depth (Fig. 10A; $R^2 = 0.981$, $n = 4$, $P < 0.01$), but it decreased in the soil from surface to 30 cm in depth. The mean ratio of $\delta^{13}C$ to $\delta^{15}N$ in mangrove soils in the IT setting was the smallest, -16.2 (Fig. 10B), and the ratio of $\delta^{13}C$ to $\delta^{15}N$ at settings CK, RV and SW was -7.9, -8.1 and -10.5, respectively.

The mixing ratio of OM in mangrove soils in Rufiji Delta grouped by tree canopy heights is presented in Fig. 11A. There were differences in the mixing ratio of marine OM (F_{mar}) among the tree canopy height classes. The mean marine OM mixing ratio (F_{mar}) was 0.50, 0.36, 0.34, 0.43, 0.37, 0.43 and 0.39 in the mangrove soils grouped by tree canopy height from H0 to H6,

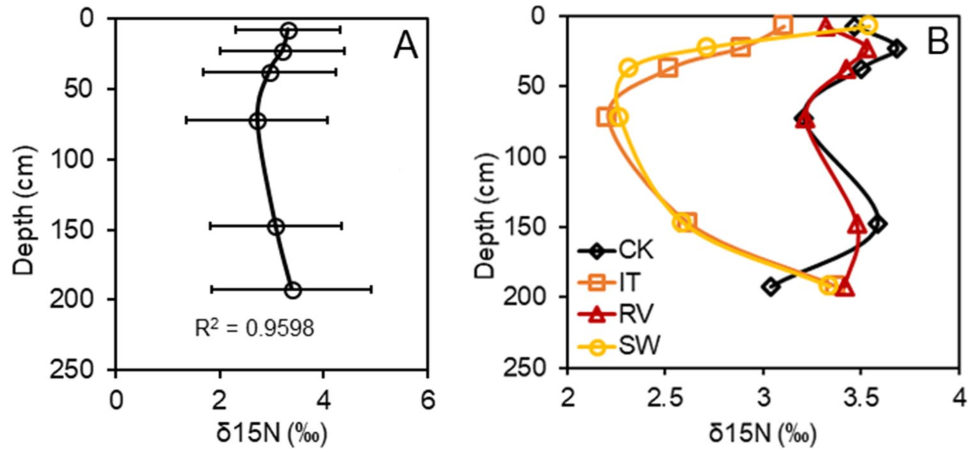

Fig. 9 Mean $\delta^{15}N$ (‰) in the mangrove soils with depth (**A**); and mean $\delta.^{15}N$ (‰) in the mangrove soils with depth for different geomorphic settings (CK: Creek; IT: Interior; RV: Riverine; SW: Seaward) (**B**)

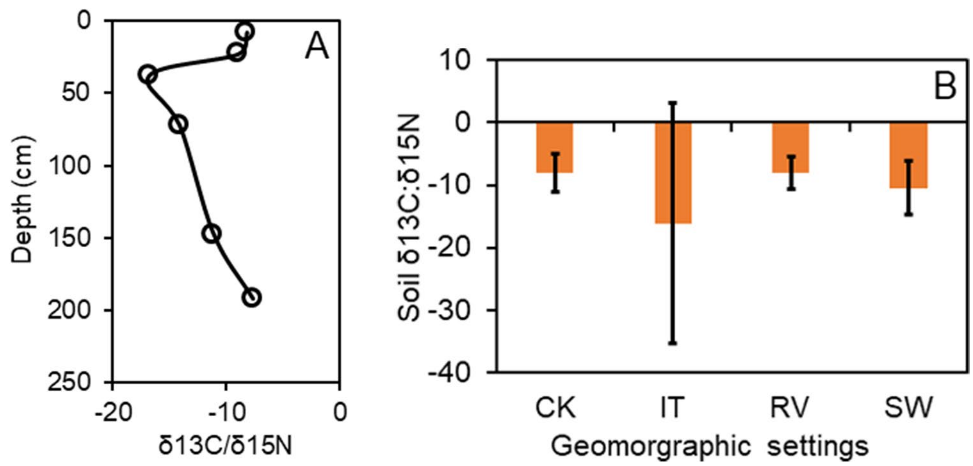

Fig. 10 Mean ratio of $\delta^{13}C$ to $\delta^{15}N$ in the mangrove soils (**A**), and the mean ratio at different settings in the mangrove soils (**B**) in Rufiji Delta; the bar is standard error (± 1 SD); CK: Creek; IT: Interior; RV: Riverine; SW: Seaward

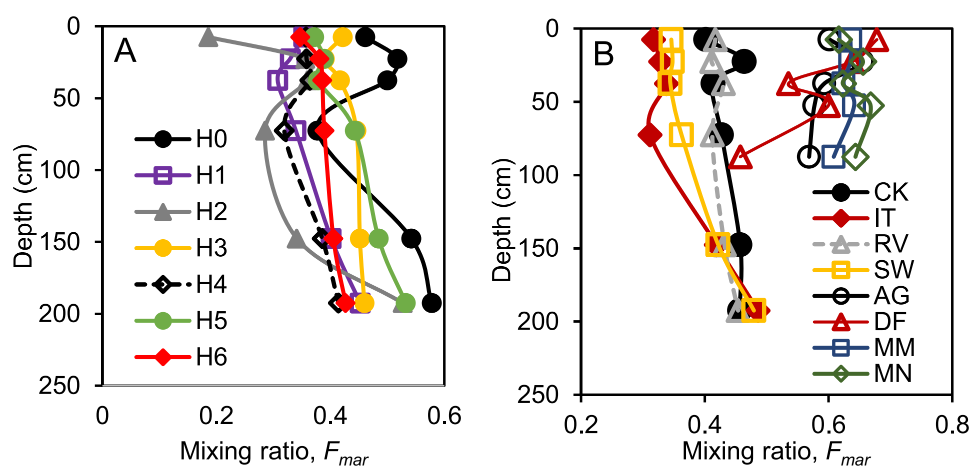

Fig. 11 Mixing ratio of marine OM sources (F_{mar}) for mangrove soils grouped by tree canopy heights, H0 – H6 (**A**); mixing ratios of marine organic sources for the mangrove and non-mangrove soils grouped by geomorphic settings (**B**); CK, IT, RV and SW for mangroves, AG, DF, MM and MN for non-mangroves

respectively. The F_{mar} over 0.50 occurred at intervals 2, 5 and 6 in H0, and at the interval 6 in H2 and H5, did not in H1, H3, H4 and H6. Accordingly, the F_{mar} value for H0 was the largest, and the values at other sampling depth intervals (1 – 3 and 5 – 6) for this tree canopy height were larger than those values at corresponding depth intervals for the tree heights from H1 to H6.

The OM mixing ratio in mangrove soils grouped by hydrogeomorphic settings showed that the ratio in CK and RV was differentiated from the other two settings (Fig. 11B).

The vertical variation in F_{mar} was similar to that in the $\delta^{15}N$, i.e., there were small differences in the F_{mar} among the sampling depth intervals in these two soil groups, CK and RV. However, the F_{mar} below 110 cm in IT and SW were larger than the values in the upper soil depth intervals, and the F_{mar} increased non-linearly with increasing soil depth from the soil surface.

The vertical variation in the mixing ratio of marine OM (F_{mar}) in RV was linearly correlated to soil depth from the mangrove surface (Fig. 11B), increased with an increment in soil depth. However, the relations between the F_{mar} and soil depth in IT and SW were quadratic. Because terrestrial mixing ratio (F_{terr}) and marine ratio (F_{mar}) are complementary (see Eq. 3), the larger the marine ratio is, the smaller the terrestrial ratio, accordingly, the vertical variation in the terrestrial ratio for each geomorphic setting in the mangroves is inverse to the relevant marine ratio.

The mixed ratio of marine organic matter (F_{mar}) in these four settings (AG, DF, MM and MN) was 0.60 ± 0.03, 0.58 ± 0.09, 0.63 ± 0.01 and 0.64 ± 0.02, respectively. Except for the F_{mar} in DF that linearly decreased small with increasing soil depth, at a mean rate of 0.26 per 100 cm from 0.68 at the interval 1 to 0.46 at the interval 5, the vertical variation of F_{mar} in other settings was smaller but statistically insignificant (see Fig. 11B).

Isotopes in Non-mangrove Soils

The soil $\delta^{13}C$ values among land cover classes were -22.0, -22.2, -21.7 and -21.6‰ in AG, DF, MM and MN, respectively, and the differences weren't significant (Fig. 12A). However, there were some and statistically insignificant differentiations in $\delta^{15}N$ among the settings, the DF has the largest $\delta^{15}N$ value (4.79‰), and AG has the smallest value (3.53‰).

The vertical variation in $\delta^{13}C$ in soils among these land cover settings was insignificant (Fig. 12B), with small differences in the mudflats (MM and MN), and slightly larger difference between AG and MM because $\delta^{13}C$ value at the interval 2 in AG was larger than the values at other intervals within this setting. Both the largest and the smallest values of $\delta^{13}C$ in these four settings occurred in a same setting, DF, indicating that the vertical changes in $\delta^{13}C$ in setting DF was large.

The vertical distribution of $\delta^{15}N$ in soils among these four hydrogeomorphic settings was slightly different (Fig. 12C). There was hardly variation in $\delta^{15}N$ in the soil

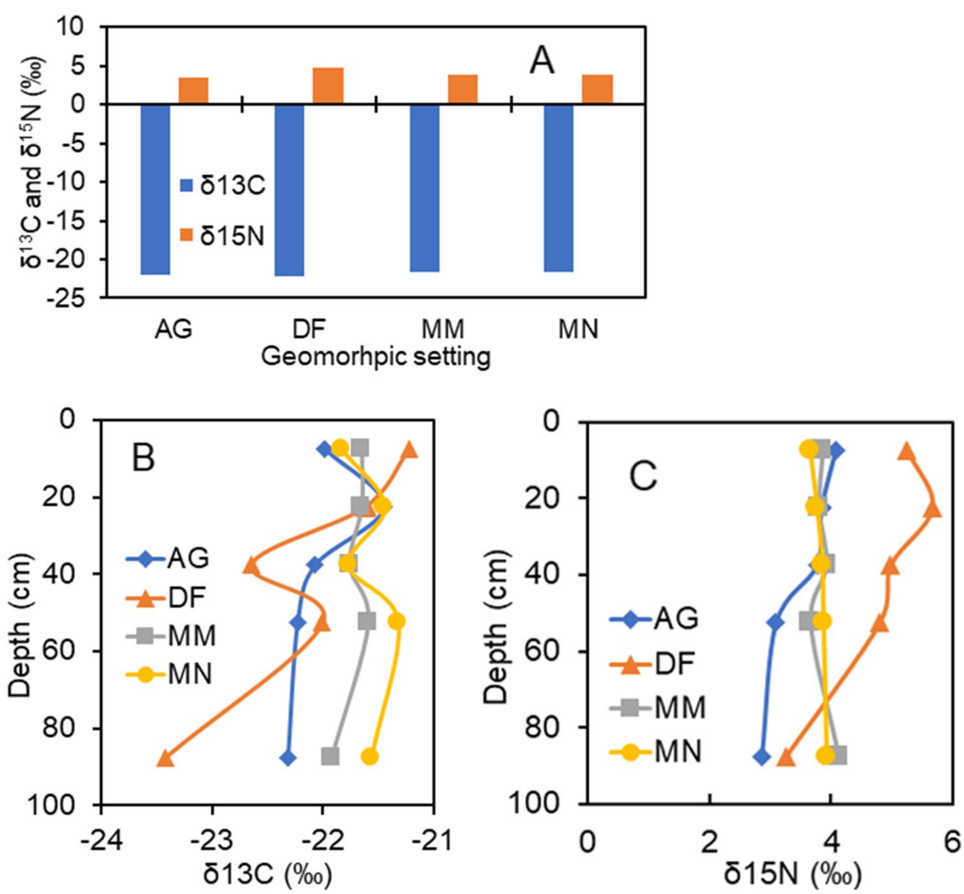

Fig. 12 The means of $\delta^{13}C$ and $\delta^{15}N$ in different geomorphic settings (**A**); AG: agricultural land (rice paddies); DF: dwarf mangrove area with very sparse stands; MM: mudflats with recently established mangroves; MN: un-vegetated mudflats; vertical variations in $\delta^{13}C$ (**B**) and $\delta^{15}N$ (**C**) in these four settings

layer from surface to 40 cm in depth in AG and then it decreased slightly. However, $\delta^{15}N$ in DF approximated a linear decrease with increasing soil depth ($R^2 = 0.8431$, $n = 5$, $P \leq 0.01$). The mean of $\delta^{15}N$ in DF was 20% higher than that in other settings, and the value at intervals 1 – 4 was higher than the values at corresponding intervals in other settings. $\delta^{15}N$ in MM and MN was hardly alteration with soil depth.

Discussion

Physical Soil Properties

The overall arithmetic and geometric spatial means and median of the BD in Rufiji Delta were 0.83, 0.82 and 0.81 (g cm^{-3}), respectively, indicating that the spatial distribution was normal. That average BD is very close to the mean (0.89 g cm^{-3}) reported by Lupembe and Munishi (2019) who sampled the same general are considered in this study. The mean BD reported here (0.83 g cm^{-3}) for Rufiji Delta is much higher than that (0.18 – 0.32 g cm^{-3}) in two mangrove sites in Micronesia (Kauffman et al. 2011), and slightly higher than the values reported for Madagascar (0.52 – 0.78 g cm^{-3}, sparse mangrove areas excluded, Jones et al. 2014), and also higher than that in a mangrove land in China (Wang et al. 2013). However, BD in this study site was similar to the density (0.84 g cm^{-3}) in Zambezi River Delta in Mozambique (Stringer et al. 2016). The difference in BD among sites is likely attributable to parent material, organic matter concentration, geomorphic setting, and sampling framework and methodologies.

In contrast to peat or organic soils where soil bulk density may be used to infer the soil carbon density (Warren et al. 2012), the mineral soils of the mangroves in the Rufiji Delta exhibited a linear relationship between BD and SOC density ($R^2 = 0.0428$, $n = 283$, $P < 0.0005$), or power function ($R^2 = 0.0917$, $n = 283$, $P < 0.0001$) that is similar to the findings of Morris et al. (2016). This is not surprising given the relatively uniform bulk density of the sediments and the narrow range of carbon concentration.

The texture of mangrove soils in Rufiji Delta was similar to that in Zambezi Delta in Mozambique with the same sampling depth, with silt accounting for about 68% (Stringer et al. 2016), and clay and sand accounting for about 16% and 16%, respectively. Clay and silt contents decreased with an increase in bulk density ($P < 0.05$ for clay and $P < 0.001$ for silt), and they were non-linearly (quadratic) correlated to SOC and TN ($P < 0.01$). The soil texture, SOC and BD in Rufiji Delta are similar to those in Zambezi Delta with the same sampling depth, reflecting the similarities between these two river deltas on the east coast of Africa.

Carbon and Nitrogen in the Mangrove Soils

Despite the relatively small variation in soil C density in mangroves within the Rufiji Delta, there are indications that stand conditions and geomorphic position influence its distribution. Soils within canopy height classes greater than 10 m (H3) tended to have a larger carbon density than in the shorter stature stands. When the plots are categorized by geomorphic position, there is a pronounced maximum in the 45 – 100 cm soil depth for each of the settings except riverine. This pattern may be caused by multiple factors, including biomass density and productivity or differential allocation from roots. The irregular distribution in riverine setting may be due to hydrological fluctuations or changes in the waterways (Punwong 2013). It's interesting to note that the interior geomorphic setting had the highest soil C density, perhaps reflecting a longer period of stability relative to locations closer to waterways. The vertical variation of SOC in the soils in the mangrove areas of Rufiji Delta might be consistent with the changes in mangrove species and the sedimentary hiatus that occurred in the interior stable locations in the delta (Punwong et al. 2013).

The average SOC for each sampling depth in Rufiji Delta, ranging from 1.86 to 46.2 mg C cm^{-3} with a spatial average of 16.35 mg C cm^{-3} and a median of 15.10 mg C cm^{-3}, are lower than those reported in the recent compilation of global mangrove sediment data (Sanderman 2017; Sanderman et al 2018). The reported data show a range of soil C density from 0.32 to 133.81 mg C cm^{-3} with a median of 28.29 mg C cm^{-3}; approximately 50% of the reports show 20 – 50 mg C cm^{-3}. Accordingly, the carbon density in the Rufiji Delta is well within the range of the published data. The soil C pool (316.9 Mg C ha^{-1} to 200 cm depth) in Rufiji Delta is similar to the soil C stock in the Zambezi River Delta (286 Mg C ha^{-1} to 200 cm; Stringer et al. 2015) but lower than the stock in Madagascar (429 Mg C ha^{-1} to 150 cm; Jones et al. 2014). Sampling to a 60 cm soil depth in the Rufiji Delta, Lupembe and Munishi (2019) reported 98.6 Mg C ha^{-1}. The soil C stock of mangroves is recognized to be the dominant C pool (Murdiyarso et al. 2009; Donato et al. 2011), but it's important that the basis for comparison be considered. For example, the reported range in a set of studies was 100 to 700 Mg ha^{-1}, but when normalized to a common depth of 100 cm, the range was 100 to 500 Mg C ha^{-1} (Stringer et al. 2015).

The spatial mean density of soil TN was 0.91 mg N cm^{-3} in this deltaic mangrove site, which is based on a TN concentration of 0.11% (dry weight basis). Accordingly, the mean TN in Rufiji Delta was similar to the mean (0.12%) in sediments in Zambezi Delta in Mozambique (Stringer et al. 2016) and the average (0.12%) from thirty-five estuaries along the west coast of India (Pradhan et al. 2014), and close to the mean of 0.13% with a range from 0.03 to 0.19% in the sediments of Pearl River estuary and adjacent shelf in south China (Hu et al. 2006). However, the TN was less than the content (> 0.2%) in the mangrove soils in the Matang Mangrove Forest Reserve in peninsular Malaysia (Alongi et al. 2004). The spatial mean of TN stored in the soils from the surface to 100 cm in Rufiji Delta was about 3.9 Mg N ha^{-1}, which was higher than the N pool (2.73 Mg N ha^{-1} within 100 cm deep soils) in mangroves in Manko Wetland in Japan (Khan et al. 2007) and lower than the N pools (10.3 and 11.7 Mg N ha^{-1}) with similar sampling depth (≤ 100 cm) in two mangroves in northern coast of Western Australia reported by Alongi et al. (2003).

The TN in the Rufiji Delta was closely correlated to SOC (Fig. 13A), increasing linearly with an increment in SOC ($R^2 = 0.4043$, $n = 283$, $P < 0.001$), indicating that the reduction in TN might be proportional to the loss rate of SOC during OM decomposition. The linear correlation between SOC and TN in the Rufiji Delta is similar to the findings of Middelburg and Herman (2007), Krishna Prasad and Ramanathan (2008) and Gireeshkumar et al. (2013). The C/N ratio (18.1 ± 5.3) in the mangrove soils in Rufiji Delta is similar to the ratios (19.8 ± 4.1) in estuarine sediments in west coast of India from 12.83°N to 23.11°N latitude (Pradhan et al. 2014) and slightly higher than the value (16.4 ± 1.4) in the sediments of the Pichavaram estuarine mangroves reported by Krishna Prasad and Ramanathan (2009).

The C:N relationship in the soils within the Rufiji Delta landscape tended to differ among the different land cover classes (Fig. 13B). The intact mangroves, comprising the geomorphic classes CK, IT, RV and SW, tended to have the highest SOC density, while the non-mangrove sites (MM, MN, AG) had higher TN density and slightly lower SOC density. The dwarf mangrove had the lowest SOC and TN density among the land cover classes.

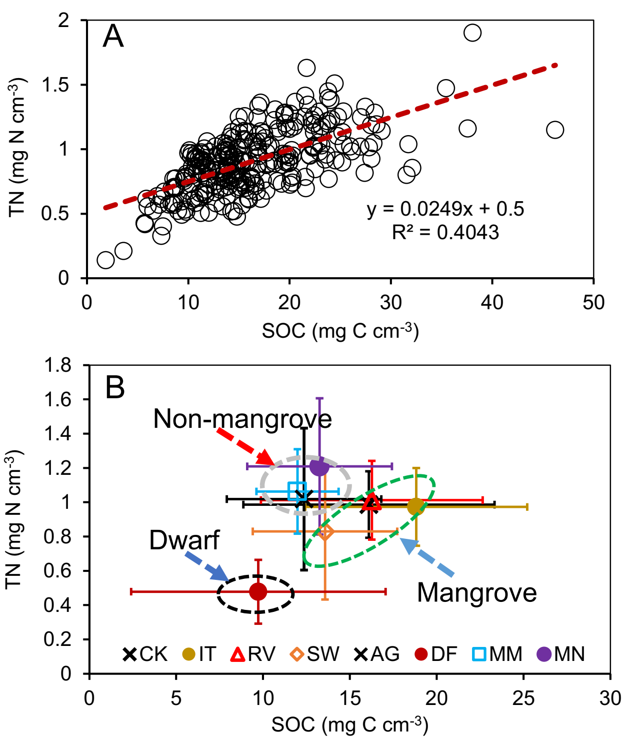

Fig. 13 Relationship between SOC and TN density in the mangrove soils in Rufiji Delta (**A**); comparison of SOC and TN in mangrove soils grouped by geomorphic settings (CK, IT, RV, SW and DF) to the relation in non-mangrove soils (AG, MN, MM) (**B**); AG: soils in agricultural lands; CK: Creek mangroves; DF: Dwarf with very sparse mangrove stands; IT: Interior mangroves; MN: mud flat without mangrove impact; MM: mud flat with recently established mangroves, SW: Seaward mangroves; RV: Riverine mangroves; sampling depth was normalized to 100 cm in depth

Sources of Carbon in the Mangrove Soils

Unvegetated, newly emerged mud flats had a SOC density of 13.25 mg C cm^{-3} as compared to forested soils that had an SOC density greater than 16.35 mg C cm^{-3}. The C stock in the mudflats demonstrate that the mangroves have developed on sites with a substantial soil C pool that had originated from marine and upstream terrestrial sources. The δ^{13}C and δ^{15}N of the soils in the Rufiji Delta cluster to reflect sites that are forested, non-forested and recently emerged and the dwarf mangrove (Fig. 14). The relative depletion of soil ^{13}C values in the mangrove sites is consistent with the norm (δ^{13}C ≤ -28‰) for mangrove tissues (Kristensen et al. 2008; Krishna Prasad and Ramanathan 2009; Gireeshkumar et al. 2013; Pradhan et al. 2014).

The δ^{13}C signature of soils across the mangrove landscape in the Rufiji Delta provided a basis for considering the relative contributions of those sources, because marine plants and organisms tend to have higher δ^{13}C values (Gireeshkumar et al. 2013; Khan et al. 2015). The SOC proportion from marine sources (F_{mar}) was higher in the mud flat soils as compared to the forested sites, reflecting a substantial contribution of marine-sourced C.

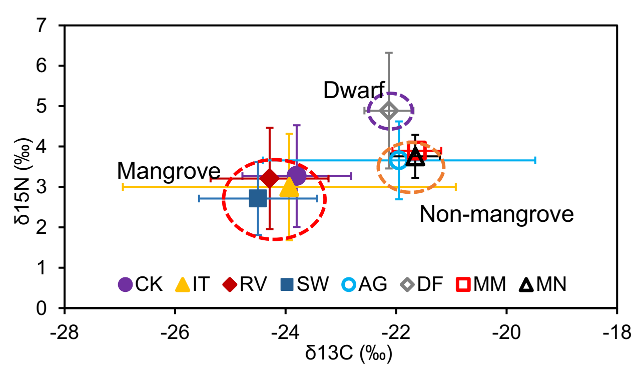

Fig. 14 Mean δ^{13}C vs. δ^{15}N in soils sampled in the sites and geomorphic positions in the Rufiji Delta

Correspondingly, the mangroves had a greater C density, with the majority of the C derived from mangroves and upstream terrestrial sources. Another indication of the contribution of mangrove-sourced C to the soil is the MM sites, although recently colonized by mangroves, their soil C density and the F_{mar} are very similar to the bare mudflat soil (MN), thereby supporting the interpretation that the higher SOC density in the mangroves is due to the long-term presence of the forest.

The interior (IT) and seaward (SW) geomorphic positions exhibited the highest F_{terr} in the upper 150 cm reflecting the influence of the mangroves on the soil pool. The riverine (RV) and creek (CK) geomorphic positions exhibited a higher proportion of F_{mar} as compared to the IT and SW, perhaps as a result of more frequent inundation or reflecting a shorter period of forest vegetation. The mixing ratio for F_{mar} at 200 cm depth in the forested sites (RV, SW, IT, CK) was much less than the mudflats (MN), reflecting the influence of mangroves throughout that soil volume. The $\delta^{13}C$ (-23.9 ± 1.4‰) in mangrove soils in Rufiji Delta might be slightly larger than the value (-26.3 ± 0.8) in the estuarine sediments in west coast of India (Pradhan et al. 2014) and slightly smaller than or close to the value (-22.36 ± 1.17‰) in Pichavaram estuarine mangrove ecosystem in eastern coast of India (Krishna Prasad and Ramanathan 2009).

The F_{mar} in dwarf mangrove (DF) at 100 cm depth was close to the values for mangrove sites, suggesting that the upper part of the solum was either recent depositional episodes or that there has been substantial alteration of the strata due to interactions with the tidal waters. The DF sites were in the seaward position, hence they may have formed in response to a storm event through deposition and altered channels. However, samples from deeper soil depths are needed from the DF to better understand their C density and the contributions of marine and forest sources. Studying three sediment cores from the Rufiji Delta, Punwong et al. (2013) showed that the mangrove species distribution over time and the age of sediments varies considerably, accordingly generalizations from these measurements are difficult.

The $\delta^{15}N$ in mangrove soils in Rufiji Delta is linearly correlated ($R^2 = 0.107$, $P < 0.001$, n = 283) to the $\delta^{13}C$. The average $\delta^{15}N$ (3.1 ± 1.3) for those soils was similar to sediments (4.66 ± 0.65) in the Pichavaram estuarine mangroves reported by Krishna Prasad and Ramanathan (2009). While the $\delta^{15}N$ of the soils in the Rufiji Delta may be influenced by different OM sources, it can be affected by other processes such as nitrification and denitrification (Middelburg and Herman 2007; Krishna Prasad and Ramanathan 2008; Wada 2009), which may explain why the relationship between $\delta^{13}C$ and $\delta^{15}N$ was weaker than the correlation between SOC and TN ($R^2 = 0.468$, $n = 283$).

Conclusions

Soils in the Rufiji Delta are silty throughout the upper 200 cm investigated in this study; they did not exhibit contrasting textural layers that is common in some fluvial systems. Relatively small changes in silt and clay content influenced the soil bulk density; and bulk density and SOC tended to vary inversely. The soil C density in the mangroves on the Rufiji Delta is within the range of reported values globally, but the median 15.10 mg C cm^{-3} is significantly less than the global median from the global data compiled by Sanderman (2017). SOC decreased nonlinearly with an increment in soil depth from the surface due to OM decomposition and translocation processes.

A river delta is a complex mosaic of erosion and depositional surfaces, which are colonized by mangroves. The soil C density of mudflats within the Rufiji Delta is 12.16 mg C cm^{-3}, demonstrating that mangrove soils contain a significant C stock prior to forest development. Within long-established mangroves the soil C density was significantly greater than bare mudflats and mudflats with recently established stands, suggesting the contribution of mangroves to the soil C stock. The distribution of SOC within established mangrove stands in RV and CK setting was less than those in IT and SW setting. The cause of these relatively small differences isn't understood. Mangrove sites converted to rice cultivation had soil C density similar to the mudflats and adjacent new developing stands, suggesting that they were developed from relatively young forested sites. Dwarf mangrove sites (DF) had a lower soil C and N densities than the long-established forests and the mudflats and recently forested sites. Clearly vegetation inputs to the soil C pools are lower on the DF sites, but why these soils have a lower C density compared to mudflats is unknown.

The contribution of marine and terrestrial (including mangroves) organic matter to the soil C stock varied significantly depending on whether the site had long-established mangroves. The OM source for the SOC in mudflats is dominated by marine sources. In contrast, SOC in the long-established mangroves was primarily from terrestrial sources, affirming that the increased SOC density of these sites is attributable to the mangroves. The mixing ratios of the DF site suggest that it has resulted from perturbation with marine-dominated sediments overlaying sediments dominated by terrestrial sources.

The model of the SOC in the Rufiji Delta that we suggest based on these findings is one where sediments have a significant C stock at the time of deposition that is derived primarily from marine sources; that soil C stock is then enhanced through the development and persistence of mangroves on the site. Unfortunately, the scale of this assessment is too coarse to address these temporal implications. Additional work is needed to affirm that the agricultural sites were indeed developed from relatively young forest stands. Similarly, the stratigraphy of the DF sites merits additional attention to better understand the role of disturbances and sea level rise on mangrove soil C stocks.

The density of C and N and the isotopic signatures explicitly imply that the mangroves in Rufiji Delta of Tanzania impact substantially the soil biogeochemistry of C and N. Accordingly, C and N density and the $\delta^{13}C$ and $\delta^{15}N$ signatures can be consistent with the landscape divisions in the Rufiji Delta, i.e., the lands with higher soil C density and lower $\delta^{13}C$ and $\delta^{15}N$ are mangroves, dwarf land with sparse dwarf mangrove stands and mudflats without vegetation are those places with lower soil C and higher $\delta^{13}C$ and $\delta^{15}N$.

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Author Contributions Carl C Trettin: funding acquisition, project design, project management, sampling design, sampling, data curation, review and editing

Mwita M Mangora: project supporting, sampling, data curation, review and editing

Wenwu Tang: software, sampling design, review and editing

Zhaohua Dai: data curation, data processing and validation, software, manuscript preparation

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Data Availability The dataset is available in Trettin CC, Dai Z, Mangora M, Lagomasino D, Lee SK, Tang W, Fatoyinbo T (2020). SWAMP Dataset-mangrove biomass soil carbon-Rufiji River Delta-2016. https://doi.org/10.17528/CIFOR/DATA.00221. Center for International Forestry Research (CIFOR), V1, UNF:6:aeysrvHQ + PbUy/FkShZmsQ = = [fileUNF].

Declarations

Competing Interests Authors have no relevant financial or non-financial interests to disclose. The authors have also declared that no competing interests exist.

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