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ORIGINAL PAPER

Soil properties of mangroves in contrasting geomorphic settings within the Zambezi River Delta, Mozambique

Christina E. Stringer · Carl C. Trettin · Stanley J. Zarnoch

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Abstract Mangroves are well-known for their numerous ecosystem services, including sequestering a significant carbon stock, with soils accounting for the largest pool. The soil carbon pool is dependent on the carbon content and bulk density. Our objective was to assess the spatial variability of mangrove soil physical and chemical properties within the Zambezi River Delta and determine whether it may be associated with geomorphic setting. Plots were classified as one of four geomorphic settings: seaward fringe, creek, riverine, and interior. Additionally, we attempted to determine the source(s) of organic matter contributing to the soil carbon pool and any associated spatial variability therein. Many statistically significant differences were shown with depth and setting. However, variability of the measured characteristics was low when compared to other mangrove settings. Mean carbon concentrations ranged from 1.38 to 2.38 % C and mean bulk density values ranged from 0.75 to 1.02 g cm^{-3}. Stable isotopic signatures showed that the organic matter is likely a mix of mangrove and marine sources, with mangrove-derived sources contributing 42–58 %.

Keywords Blue carbon · Forested wetland · Organic matter · Soil carbon · Soil nitrogen · Zambezi River Delta

C. E. Stringer (✉) · C. C. Trettin
Center for Forested Wetlands Research, Southern Research Station, USDA Forest Service, Cordesville, SC, USA
e-mail: christinaestringer@fs.fed.us

S. J. Zarnoch
Forest Inventory and Analysis, Southern Research Station, USDA Forest Service, Clemson, SC, USA

Introduction

Mangrove ecosystems are recognized as having the capacity to contain higher carbon (C) density than any terrestrial ecosystem (Alongi 2014). The soil within mangrove forest is the largest C pool (Donato et al. 2011), typically 2–4 times greater than the tree biomass C pool. The relatively large soil C pool is a function of the C density (e.g., soil C content (%) and soil bulk density) and the depth of consideration. The average soil organic C content, based on a literature review of published data, is 2.2 %, with a large range of less than 0.1 % to greater than 40 % (Kristensen et al. 2008), indicating substantial differences among sites. Similarly published soil bulk density values range from 0.18 g cm^{-3} in organic soils (Kauffman et al. 2011) to 1.26 g cm^{-3} in mineral sediments (Jones et al. 2014).

The principal factor affecting the soil C pool in mangroves is the high C density throughout the profile or assessment depth. In contrast, most terrestrial forest soils exhibit a distinct decline in C content within the

upper 100 cm of the soil. Most of the organic matter input is on the soil surface and upper 50 cm of soil where it is subsequently decomposed and retranslocated within the solum. The high C density with depth in mangroves is attributed to high organic matter input rates from the mangroves and sedimentation, as well as low decomposition rates (Bouillon et al. 2008; Kristensen et al. 2008). Both macro- and micro- algae are also recognized as an important organic matter source in mangroves (Kristensen et al. 2008; Sukardjo et al. 2013). Accordingly, soil C accumulating in mangrove sediments may be derived from autochthonous or allochthonous sources, varying with depth (Saintilan et al. 2013) and may also exhibit spatial variability depending on landscape position.

As developing nations prepare to be involved with incentive programs for climate change mitigation, such as the UN's Reducing Emissions from Deforestation and Degradation and Enhancement of Carbon Stocks (REDD+) program, there is increasing interest in the inclusion of mangroves in national climate change mitigation and adaptation plans. The inclusion of mangroves in incentive programs will rely on the quality of the C store estimates and a better understanding of the drivers affecting the variability of soil C (Saintilan et al. 2013). Our objective was to assess the spatial heterogeneity of soil characteristics within the Zambezi River Delta and determine whether it may be associated with geomorphic setting: seaward fringe, creek, riverine, and interior. Additionally, we attempted to determine the source(s) of organic matter contributing to the soil C pool and any associated spatial variability therein. We hypothesized that characteristics and organic matter sources would be different between each delineated setting, due to the varying degree of hydrologic connectivity with the terrestrial (upstream) and marine (offshore) environments. Specifically, we thought that the riverine plots would show the largest concentration of soil C and N, with a distinct terrestrial signature, while the seaward fringe plots would have the lowest soil C and N, with a distinctly marine signature.

Methods

Study area

The Zambezi River Delta (Fig. 1) comprises an area of approximately 12,000 km^2, extending 120 km downstream of the Zambezi and Shire Rivers confluence to the Indian Ocean. It also extends 200 km southwest-northeast along the coastline, from the Cuacua River, to the Zuni River Delta. The climate of the region is tropical, with a distinct dry winter season from April to October and a wet summer season from October to April (Barbosa et al. 2001; Hoguane 2007). The mean annual precipitation is around 1400 mm along the coast, with considerable inter-annual variation (Bento et al. 2007). The majority of the rain (85 %) falls from mid-November to late March (Tweddle 2013). Mean monthly temperatures range from 27 °C to 37 °C (Tweddle 2013).

The water levels in the Zambezi River Delta are reflective of the cumulative runoff patterns in the upstream sub-basins, with an estimated average water volume of 108×10^9 m^3 reaching the Delta on an annual basis (Beilfuss and Santos 2001). The tidal regime is semi-diurnal, with a spring tide maximum amplitude of 4.1 m (Beilfuss and Santos 2001; Coleman 2004). This tidal range is the largest in Mozambique and in the dry season tidal influence reaches 80 km upstream (Beilfuss and Santos 2001).

The geomorphology of the Delta is thought to be affected by upstream activities and water flows, especially the operation of the Kariba and Cahora Bassa Dams. The dams have not only reduced freshwater discharge to the Delta, but also diminished sediment transport, resulting in coastal zone erosion and a reduction of sediment-maintained habitats, including mangroves (Davies et al. 2000). The degree to which these changes in flows and deposition directly affect the vegetative communities, including mangroves, within the Delta has not been well studied.

Within the widely-utilized mangrove hierarchical classification system (Twilley et al. 1998), the Zambezi River Delta mangrove complex as a whole can be considered a deltaic environmental setting. The mangrove occurs on mud flats within the coastal estuary, occupying an area of approximately 30,267 ha, as delineated by Fatoyinbo and Simard (2013) (Fig. 1). There are eight mangrove species present in the Delta, representative of all species reported to occur in Mozambique: *Sonneratia alba* Smith, *Avicennia marina* (Forsskk.) Vierh., *Rhizophora mucronata* Lam., *Ceriops tagal* (Per.) C.B. Robinson, *Bruguiera gymnorrhiza* (L.) Lam., *Lumnitzera racemosa* Wild., *Heritiera littoralis* Alton, and *Xylocarpus granatum* Koenig.

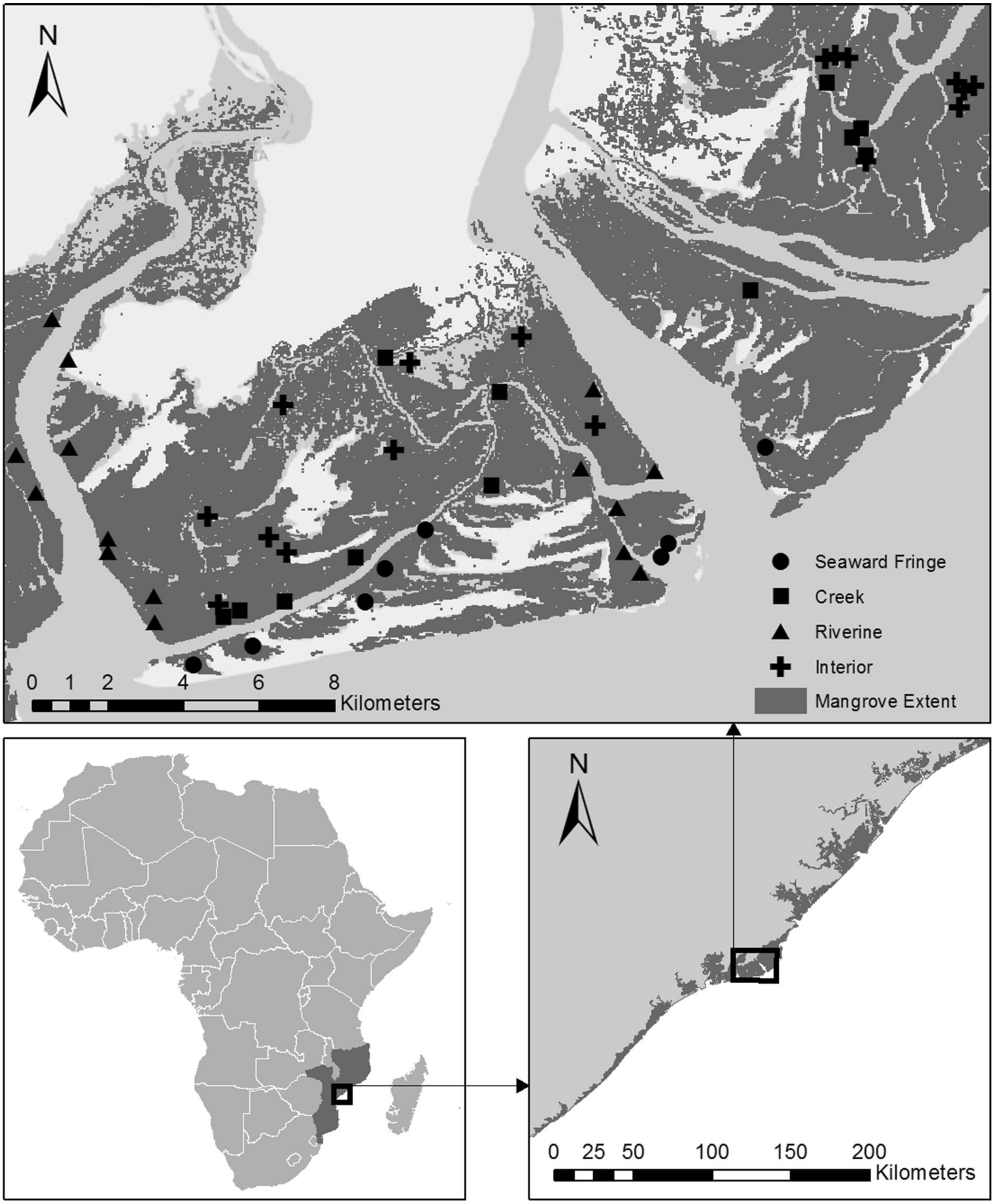

Fig. 1 The study area and its position on the Mozambican coast. The mangrove extent (Fatoyinbo and Simard 2013) is represented by dark gray shading. The plots are represented by their respective geomorphic setting classification

Table 1 Mangrove stand characteristics means (S.E.) for each geomorphic setting

Setting	DBH (cm)	Height (m)	Basal Area (m^2 ha^{-1})	Dominant species
Seaward fringe	9.37 (0.30)	7.53 (0.51)	14.81 (4.19)	*X. granatum* (0.51)
Creek	9.20 (0.68)	7.96 (0.99)	16.96 (2.82)	*X. granatum* (0.39)
Riverine	15.06 (1.44)	12.35 (1.72)	34.74 (5.39)	*B. gymnorrhiza* (0.42)
Interior	10.78 (0.94)	11.90 (0.68)	22.50 (3.77)	*A. Marina* (0.30)

The number in parentheses after the name of each dominant species indicates the proportion of the total basal area in that setting represented by the species

Sampling design

A large scale C stock inventory was conducted in the Zambezi River Delta in 2012 and 2013 (Stringer et al. 2015). Our inventory utilized a stratified random sampling approach based on canopy height class, using 7 m radius subplots (0.0154 ha) nested within a 0.52 ha square plot. During the first field season, 12 plots containing 6 subplots each were sampled. Analysis of the 2012 data demonstrated that the number of subplots could be reduced to 5 with an acceptable loss of precision, so the number of subplots sampled in 2013 was reduced to 5 in each of the 40 plots established. Thus, over the course of the two sampling efforts, a total of 52 plots were established and sampled.

The existing plots used in that inventory were reclassified into 4 geomorphic settings: seaward fringe, creek, riverine, and interior. These settings were delineated based on their hydrologic connectivity with both upstream and marine sediment sources and potential sediment accommodation space, following the ecological types delineated by Twilley et al. (1998), based on topographic location and hydroperiod at the local scale (Lugo and Snedaker 1974). The seaward fringe sites ($n = 8$) were plots located closest to the ocean, in which mangroves occurred intermittently with sandy areas dominated by palms and grasses. The creek sites ($n = 12$) were plots located directly adjacent to a small, perennial channel or creek, with low flows and only intermittent tidal effects. Riverine sites ($n = 15$) were located directly along one of the two main tributary channels of the Zambezi River, exposed to high energy water movement and large flows. Interior sites ($n = 17$) were located in the middle of the mangrove, with no direct connectivity to surface water sources.

Forest characteristics (diameter at breast height, tree height, and basal area) from each plot (Trettin et al. 2015) were obtained to characterize general mangrove structure and composition for each geomorphic setting (Table 1). A heterogeneous mix of species was found at both the plot and setting levels, with 5 or more mangrove species occurring within each setting.

Sample collection

Soil was sampled to a depth of 200 cm from a point near the center of each subplot using a stainless steel gouge auger with a semi-cylindrical chamber 1 m long and 18.8 cm^2 in cross-sectional area (AMS Inc, American Falls, Idaho, USA). Soils were sampled at 6 core depth intervals, with a 5 cm section of the soil core, measured to the nearest mm, obtained at 5–10 cm (depth interval 1), 20–25 cm (depth interval 2), 35–40 cm (depth interval 3), 70–75 cm (depth interval 4), 145–150 cm (depth interval 5), and 190–195 cm (depth interval 6), respectively.

Sample processing and laboratory analyses

The samples were returned to a laboratory and dried at 60 °C until a constant weight was achieved. The air-dried mass of the soil samples was adjusted to oven-dried mass by applying the mean air-dried to oven-dried ratio (1.010 ± 0.003), determined by drying a subset of 50 samples at 105 °C. The bulk density (g cm^{-3}) of each sample was calculated by dividing the oven-dried mass by the volume of the sample. A subset of 50 samples was tested for the presence of carbonates through the observation of the reaction of the sample with trace-metal grade hydrochloric acid, following Thomas (1996); none tested positive. Oven-

dried samples were coarse ground and then pulverized using a high-energy ball mill (SPEX SamplePrep, Metuchen, NJ, USA). No additional sieving was needed to prepare samples for analyses.

Soil texture was characterized for two plots randomly selected from each of the 4 settings (total of 8 plots). Limited resources necessitated a small sample population for this analysis. Within each selected plot, the core from one subplot was randomly selected for analysis. All soil texture analyses were completed at the University of Nevada, Las Vegas Environmental Soil Analysis Laboratory. Approximately 0.2 g of each sample was soaked in 5 ml of deionized water for 24 h, and dispersed with ultrasound for 5 min right before analysis. All particle size analyses were done with a Malvern Mastersizer 2000 laser particle size analyzer equipped with a Hydro S dispersant unit (Malvern 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). Three replications were analyzed for each sample.

Organic matter content was analyzed for the same subset of 8 plots selected for the soil texture analysis. Determination was made by the loss-on-ignition method, ashing at 500 °C for 6 h, following Nelson and Sommers (1996). The C and nitrogen (N) concentrations of each soil sample from all 52 plots were determined at the University of Georgia Analytical Chemistry Laboratory. Pulverized subsamples were analyzed using a Carlo Erba, NA1500 CHN Analyzer (Carlo Erba Strumentazione, Milan, Italy) via a Thermo Conflo III open split interface. Duplicates were analyzed for quality assurance, producing standard deviations ±0.2 % and ±0.02 % or lower for C and N concentrations, respectively.

Carbon and N isotopic signatures of soil samples were determined for a subset of 18 plots: 4 plots from each of the seaward fringe, riverine and creek settings; and 6 plots from the interior setting. Analyses were completed using a Thermo Delta V stable isotope ratio mass spectrometer (Thermo Fisher Scientific Inc., Bremen, Germany), coupled to the CHN analyzer described above. The instrumental error for both $\delta^{13}C$ and $\delta^{15}N$ was ± 0.08 ‰. Duplicate sample standard deviations for $\delta^{13}C$ and $\delta^{15}N$ were ± 0.2 ‰ and ± 0.6 ‰ or lower, respectively. Isotopic signatures are reported in conventional delta notation (δ):

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \times 1000$$

where R_{sample} is either $^{13}C/^{12}C$ or $^{15}N/^{14}N$ and $R_{standard}$ is the isotope ratio of either Pee Dee Belemnite (PDB) limestone or atmospheric N_2.

A simple, two end-member mixing model was utilized to estimate the relative contributions of terrestrial/mangrove and marine (phytoplankton and seagrass litter) organic matter inputs, following Ranjan et al. (2011). Constant end-member values of $\delta^{13}C$ were used for both organic matter end members: −28 ‰ and −18 ‰ for terrestrial/mangrove and marine sources, respectively (Ranjan et al. 2011). The marine fraction was calculated using the following equations:

$$f_{mar} = \frac{\delta^{13}C_{man} - \delta^{13}C_s}{\delta^{13}C_{man} - \delta^{13}C_{mar}}$$

$$f_{man} = 1 - f_{mar}$$

where f_{mar} is the marine organic matter fraction, f_{man} is the terrestrial/mangrove fraction, $\delta^{13}C_s$ is the values of the sediment, and $\delta^{13}C_{man}$ and $\delta^{13}C_{mar}$ are end-member values for mangrove and marine sources, respectively.

Statistical analyses

All statistical analyses were performed using SAS (SAS Inc. 2011). A repeated measures analysis in space was conducted with Proc Mixed to evaluate the fixed effects of geomorphic setting and sampling depth interval, as well as their interaction, on soil bulk density and geochemical characteristics. Plots and subplots nested within plots were random factors, with subplots being the subject upon which the repeated measures with depth were taken. Several covariance structures were modeled, including variance components, compound symmetry, autoregressive (1), and spatial power, and evaluated using the Akaike Information Criterion Corrected (AICC). For most variables the spatial power covariance structure yielded the best (lowest) AICC. In addition, the repeated measure factor was depth with unequally-spaced levels, so the spatial power covariance structure was

considered most appropriate to represent the correlation between the depths.

Assumptions were judged by inspecting frequency histogram plots of residuals and plots of residuals over predicted. For all analyses, the residuals were normally distributed and did not show any pattern with the predicted. Least-square means were obtained for the main effects of settings and depth and tested with the Tukey–Kramer multiple comparison procedure at an experimentwise Type I error rate of 0.05. However, when a significant interaction was detected the individual setting-depth least square means were obtained and the slice option was used to test for differences between depths within each setting. If a significant F-test resulted at the 0.05 level, then all possible 15 pairwise comparisons between the 6 depths for the setting were performed as *t* tests and significance was determined using the Bonferroni adjustment critical value of $0.05/15 = 0.0033$.

Results

Soil physical properties

Each of the soil characteristics, other than sand and silt content, exhibited statistically significant differences for either one or both main effects tested (Table 2). Significant interaction effects between setting and depth interval occurred for bulk density, C concentration, C density, and clay content. The interactions observed for the bulk density, % C and C density are all due to different depth trends for those characteristics within the seaward fringe as compared to the other 3 settings (Figs. 3a–c). The interaction observed for the % clay variable is believed to have occurred due to small sample size 8 plots), which resulted in statistical significance but actually represented a Type I error at the 0.05 level, and does not reflect a meaningful interaction (Table 2).

Disregarding the interaction described above, depth trends in the % clay in the soil texture among geomorphic settings are quite similar (Fig. 2a). All samples were classified as a Silt Loam, with silt accounting for 68 % or greater of the soil composition (Fig. 2c). The highest sand content occurred in the deepest sampling depth interval in the riverine geomorphic setting (Fig. 2b). Within the sand component, particle size was dominated by the very fine and fine fractions, the sum of which accounted for 82 % or greater of the sand composition for each setting.

Bulk density ranged from 0.75 g cm^{-3} in the shallowest samples of the interior and creek settings to 1.02 g cm^{-3} in the seaward fringe setting, with an overall mean of 0.84 g cm^{-3} (Table 3; Fig. 3a). Bulk density within the seaward fringe and creek settings showed no significant differences with depth. For interior setting, depth interval 1 was significantly different than depth intervals 5 ($p = 0.0006$) and 6 ($p < 0.0001$). Within the riverine setting, the mean for depth interval 4 was significantly different from interval 6 ($p = 0.0059$).

Carbon and nitrogen content

Carbon concentration had an overall mean of 1.81 % C, ranging from 1.38 % C in the seaward fringe to 2.38 % C in the interior (Table 3; Fig. 3b). The depth means for the seaward fringe, creek, and riverine

Table 2 P values resulting from repeated measures analysis type 3 tests of fixed effects

Variable	Setting	Depth interval	Setting × depth interval
Bulk density	**0.0027**	**0.0077**	**0.0002**
%C	**0.0528**	**<.0001**	**0.0090**
Carbon density	0.6756	**<.0001**	**0.0260**
%N	0.6253	**0.0001**	0.8904
cn ratio	**0.0093**	**<.0001**	0.7701
$\delta^{13}C$	**0.0456**	**0.0076**	0.4113
$\delta^{15}N$	**0.0078**	**<.0001**	0.1804
Sand fraction	0.5251	0.5338	0.4886
Silt fraction	0.4751	0.5922	0.6102
Clay fraction	**0.7344**	**0.0073**	**0.0146**

Values in bold indicate a statistically significant effect at $p = 0.05$

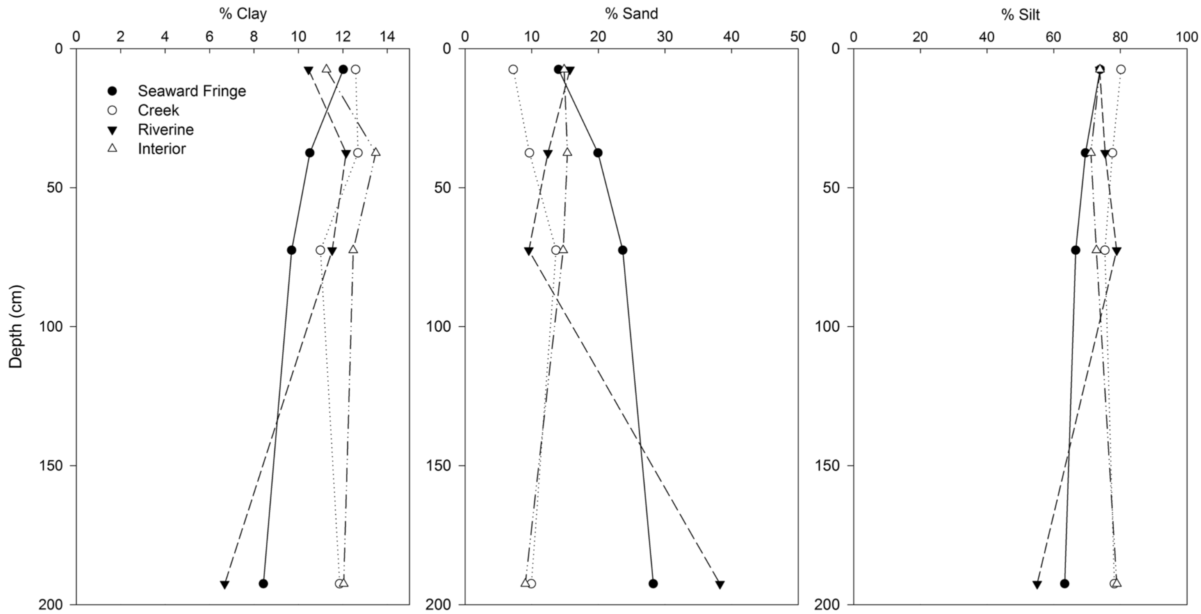

Fig. 2 Mean soil texture composition with depth: % clay (**a**), % sand (**b**), and % silt (**c**) for each geomorphic setting

settings did not vary with depth. Within the interior setting, depth interval 1 was significantly different from all of the other depth intervals ($p \leq 0.0001$ for all tests). Additionally, interior setting depth interval 6 was significantly different from 2 ($p = 0.015$), and 3 ($p = 0.0028$).

Carbon density generally decreased with depth and had an overall mean of 0.014 g C cm^{-3}, ranging from 0.012 g C cm^{-3} in the riverine depth interval 6 to 0.017 g C cm^{-3} in the interior depth interval 1 (Table 3; Fig. 3c). Within the creek setting, depth interval 4 was significantly different from depth interval 6 ($p = 0.03$). In the riverine setting depth interval 1 was significantly different than depth intervals 2 ($p = 0.02$), and 6 ($p = 0.0003$). Depth interval 1 in the interior setting was significantly different than the other 5 depth intervals ($p \leq 0.005$ for all tests).

Nitrogen content did not vary with setting and had an overall mean of 0.13 % N (Table 3; Fig. 3d). The N content varied significantly with depth only within the interior setting, where depth interval 1 was significantly different from interval 4 ($p = 0.009$) and 5 ($p = 0.03$). The C:N exhibited the greatest difference between the seaward fringe (14.28) and interior settings (17.35) ($p = 0.03$). Depth means within the seaward fringe and riverine settings showed no significant difference with depth (Table 3). Within the creek setting, depth interval 4 was significantly different from depth intervals 1 ($p = 0.0035$) and 2 ($p = 0.04$) (Table 3; Fig. 3e). The overall C:N mean for entire study area was 15.54.

The relationship between organic matter and C content was linear ($R^2 = 0.81$) with the ratio of organic matter to C concentration ranging from 3.36 to 5.97 (Fig. 4a). Bulk density and % C exhibited the typical, well-known inverse relationship, which was represented quantitatively using a power function ($R^2 = 0.73$) (Fig. 4b).

Isotopic Composition

Only the seaward fringe and interior geomorphic settings, which had the highest and lowest $\delta^{13}C$ values, respectively, were significantly different with respect to the C isotopic composition ($p = 0.045$). With the exception of the second sampling depth interval (20–25 cm below ground surface), the $\delta^{13}C$ means increased down core from −23.83 ‰ to −22.86 ‰, but did not vary significantly (Fig. 5a). The mean N isotopic composition of the seaward fringe sites (4.74 ‰) was significantly higher than that of the other settings ($p \leq 0.03$). The $\delta^{15}N$ value decreased from 4.59 ‰ to 3.61 ‰ with core depth, exhibiting significant differences among depth means ($p \leq 0.0001$ for all tests) (Fig. 5b).

Table 3 Soil characteristic means (S.E.) by depth within each geomorphic setting

	Depth interval	Seaward fringe mean (SE)	Creek mean (SE)	Riverine mean (SE)	Interior mean (SE)
Bulk density (g cm^{-3})	1 (5–10 cm)	0.99 (0.04) a	0.75 (0.04) a	0.81 (0.03) ab	0.75 (0.03) a
	2 (20–25 cm)	0.98 (0.04) a	0.77 (0.04) a	0.77 (0.03) ab	0.78 (0.03) ab
	3 (35–40 cm)	1.02 (0.04) a	0.75 (0.04) a	0.77 (0.03) ab	0.79 (0.03) ab
	4 (70–75 cm)	0.96 (0.05) a	0.75 (0.04) a	0.75 (0.03) a	0.80 (0.03) ab
	5 (145–150 cm)	0.96 (0.05) a	0.80 (0.04) a	0.84 (0.03) ab	0.87 (0.03) bc
	6 (190–195 cm)	0.90 (0.05) a	0.78 (0.04) a	0.87 (0.04) b	0.90 (0.03) c
% Carbon	1 (5–10 cm)	1.64 (0.16) a	2.14 (0.13) a	2.08 (0.11) a	2.38 (0.11) a
	2 (20–25 cm)	1.44 (0.16) a	1.88 (0.13) a	1.87 (0.11) a	1.98 (0.11) b
	3 (35–40 cm)	1.56 (0.16) a	2.07 (0.13) a	1.92 (0.11) a	2.01 (0.11) b
	4 (70–75 cm)	1.38 (0.16) a	2.22 (0.13) a	1.89 (0.11) a	1.93 (0.11) bc
	5 (145–150 cm)	1.58 (0.18) a	1.87 (0.13) a	1.70 (0.12) a	1.73 (0.11) bc
	6 (190–195 cm)	1.48 (0.2) a	1.75 (0.14) a	1.52 (0.13) a	1.56 (0.12) c
Carbon density (g C cm^{-3})	1 (5–10 cm)	0.015 (0.001) a	0.015 (0.001) ab	0.016 (0.001) a	0.017 (0.001) a
	2 (20–25 cm)	0.014 (0.001) a	0.014 (0.001) ab	0.014 (0.001) b	0.015 (0.001) b
	3 (35–40 cm)	0.015 (0.001) a	0.015 (0.001) ab	0.014 (0.001) ab	0.015 (0.001) b
	4 (70–75 cm)	0.013 (0.001) a	0.016 (0.001) a	0.014 (0.001) ab	0.014 (0.001) b
	5 (145–150 cm)	0.014 (0.001) a	0.015 (0.001) ab	0.014 (0.001) ab	0.014 (0.001) b
	6 (190–195 cm)	0.013 (0.001) a	0.013 (0.001) b	0.012 (0.001) b	0.013 (0.001) b
% Nitrogen	1 (5–10 cm)	0.13 (0.04) a	0.15 (0.03) a	0.21 (0.02) a	0.22 (0.02) a
	2 (20–25 cm)	0.11 (0.03) a	0.13 (0.03) a	0.14 (0.02) a	0.13 (0.02) ab
	3 (35–40 cm)	0.11 (0.03) a	0.13 (0.03) a	0.16 (0.02) a	0.17 (0.02) ab
	4 (70–75 cm)	0.09 (0.04) a	0.12 (0.03) a	0.12 (0.02) a	0.11 (0.02) b
	5 (145–150 cm)	0.10 (0.04) a	0.11 (0.03) a	0.11 (0.03) a	0.11 (0.03) b
	6 (190–195 cm)	0.12 (0.05) a	0.11 (0.03) a	0.10 (0.03) a	0.14 (0.03) ab
C:N	1 (5–10 cm)	12.80 (1.22) a	13.95 (0.94) a	13.61 (0.86) a	14.52 (0.81) a
	2 (20–25 cm)	13.71 (1.2) a	14.65 (0.95) a	13.76 (0.86) a	15.86 (0.81) ab
	3 (35–40 cm)	14.36 (1.21) a	15.96 (0.94) ab	14.63 (0.86) a	17.71 (0.81) bc
	4 (70–75 cm)	14.87 (1.23) a	18.30 (0.94) b	15.35 (0.87) a	19.50 (0.82) c
	5 (145–150 cm)	15.34 (1.46) a	16.60 (1.01) ab	15.14 (0.93) a	18.43 (0.87) bc
	6 (190–195 cm)	14.61 (1.65) a	15.87 (1.06) ab	15.29 (1.01) a	18.08 (0.93) abc

Within each setting, depth means followed by the same letter are not significantly different at $p = 0.05$, based on individual two-sample *t* tests

Mass-balance mixing model

The isotopic signature of the soil C and N could be attained by a mixture of organic matter sources (Fig. 6). The two end-member mixing model, using $\delta^{13}C$ as a tracer, showed the proportion of terrestrial/mangrove organic material in the seaward fringe setting was 0.42 and significantly different from the others ($p = 0.03$). The other 3 settings were similar to each other and had mangrove organic matter proportions of 0.56 to 0.58. The proportion of mangrove organic matter decreases down-core, from 0.58 at the top depth interval to 0.49 at 2 m.

Discussion

The mean soil C content determined for the Zambezi River Delta (1.81 % C) was similar to both Madagascar (3.4 %) (Jones et al. 2014) and the mangrove

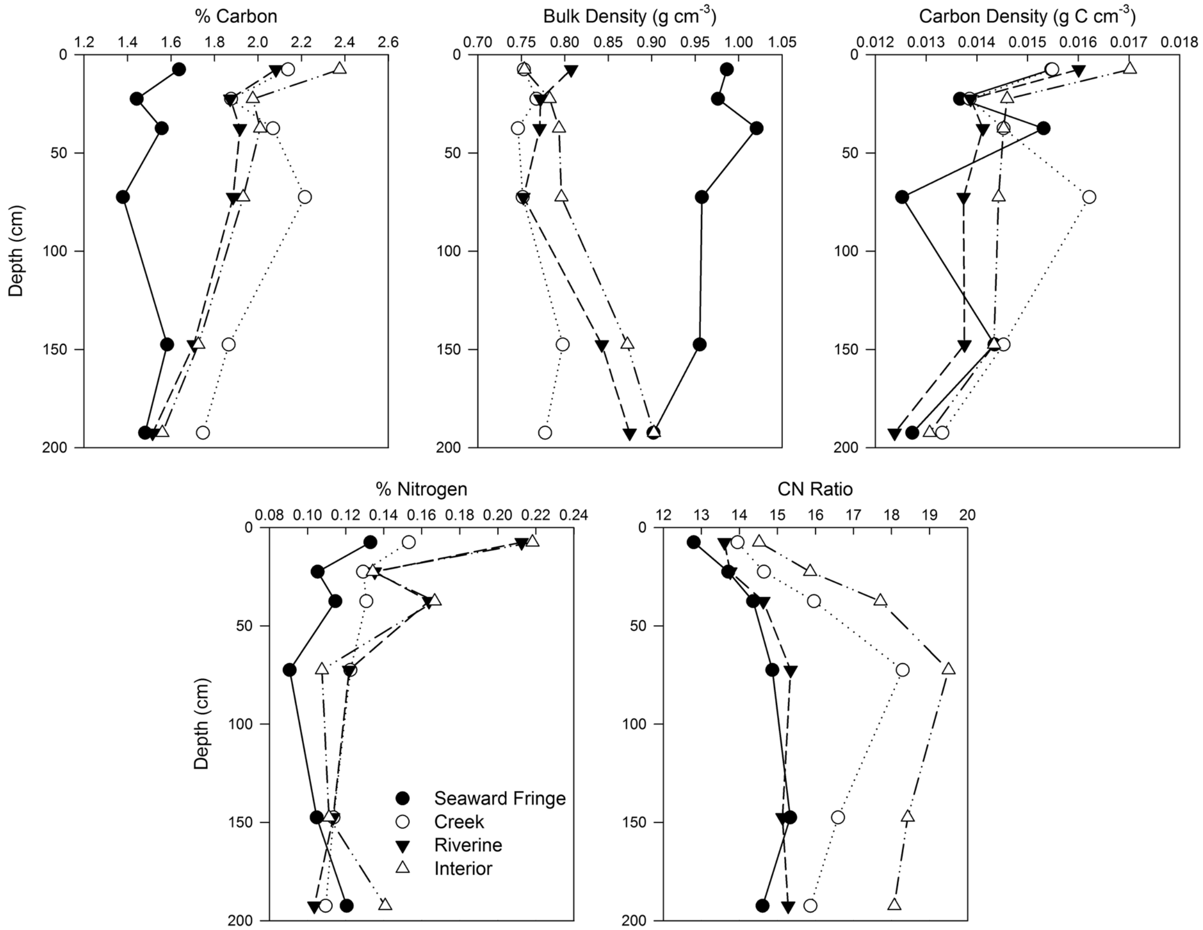

Fig. 3 Mean soil bulk density and geochemical characteristics with depth for each geomorphic setting

global median of 2.2 % (Kristensen et al. 2008). In contrast, several recent studies report mangrove soil C concentrations ranging from 9 to 26 % (Donato et al. 2012; Kauffman et al. 2011; 2014; Wang et al. 2013). Mangrove soil bulk density has not been synthesized across the literature and is sometimes not directly discussed. Previous studies report mean bulk density values ranging from 0.18 g cm^{-3} (Kauffman et al. 2011) to 1.26 g cm^{-3} (Jones et al. 2014), encompassing the mean value for the Zambezi (0.84 g cm^{-3}). Soil C density was shown by Chmura, et al. (2003) to range from 0.023 g C cm^{-3} to 0.114 g C cm^{-3} for mangrove soils from the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterranean Ocean, and Gulf of Mexico. The mean C content for this study, 0.014 g C cm^{-3}, was slightly below this global estimate and similar to Madagascar, which had a mean of 0.026 g C cm^{-3} (Jones et al. 2014). While soil C density can be a useful criterion to facilitate study inter-comparisons, it can also obscure differences in soil characteristics, as extremes in the two input parameters that determine C density (bulk density and % C) often counterbalance each other to produce similar values, as was the case in the means of the seaward fringe and interior settings in this study.

The relationship between soil OM and C content exhibited a reasonably-strong linear relationship, but was quite different from the correlation exhibited in other mangrove soil studies (Kauffman and Donato 2012) and the general idea that OM contains about 58 % C (Howard 1965). The mean relationship shown here suggests that C comprises only 21 % of soil OM and that the appropriate conversion factor would be 4.77, more than double the commonly-used factor of

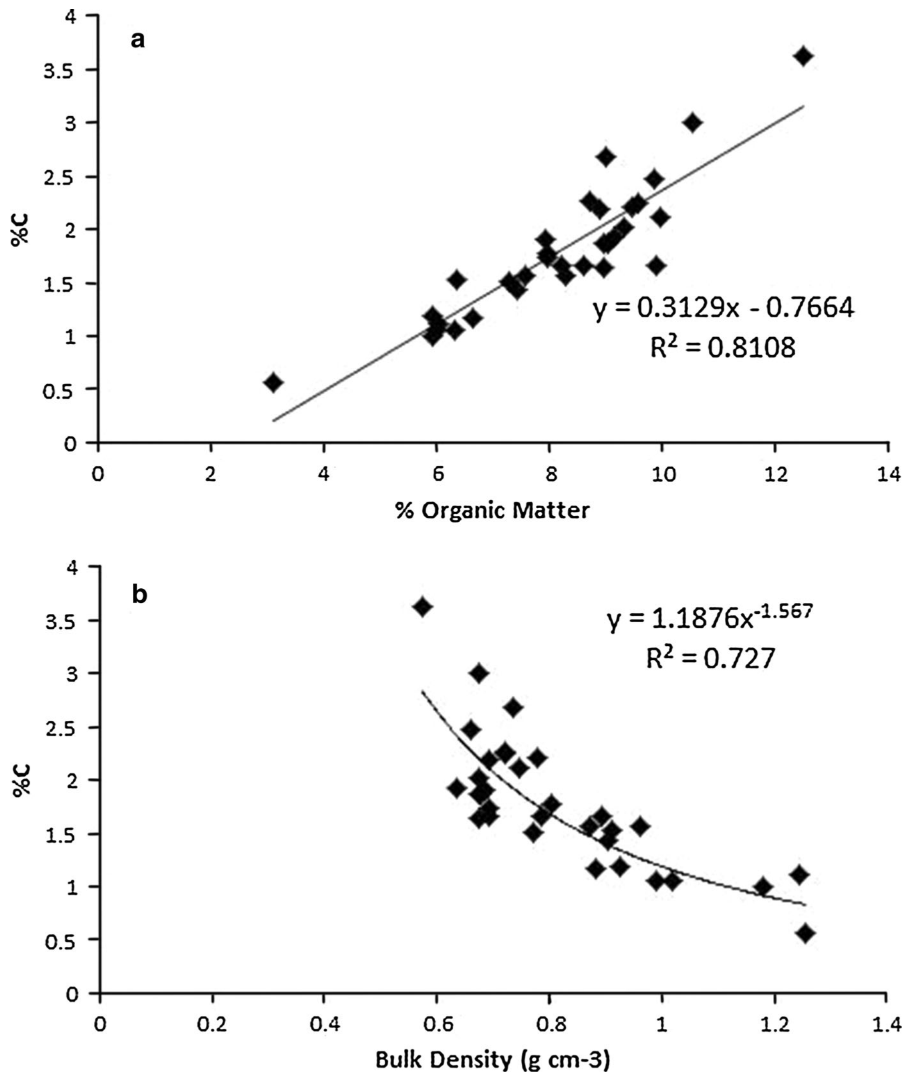

Fig. 4 Relationship between physical and chemical soil properties: **a** % organic matter and % C and **b** bulk density and % C

1.724 (Chmura et al. 2003; Howard 1965). This discrepancy illustrates the caution that must be taken when the LOI approach is used to estimate soil C and the importance of the soil type as a consideration that must be taken into account when determining a study approach. Additionally, this difference shows that a conversion factor based on site- or region-specific data is the best option to use when possible.

The underlying premise of this study was that the variation in the hydrologic connectivity and potential sediment accommodation space among these settings would be an important control on the quantity and source of the C stored. Our hypothesis was upheld, as there were many statistically significant differences between settings. The Sundarbans mangrove, another large deltaic system, also exhibited variations in soil C amongst both soil types and salinity zones (Rahman et al. 2014). The mangroves of Gazi Bay, Kenya, a lagoon setting, had wide variations in soil C and N: from 0.3 to 18 % C and 0.01 to 3.5 % N, suggesting that the differences in soil characteristics, including soil texture and organic C and N content, were due to differences in forest type (Middelburg et al. 1996). Saintilan et al. (2013) found that geomorphic setting exerted an influence on C store, reporting that their study sites located on sandy marine deltas supported significantly lower C stores, while fluvial environments exhibited a greater retention of C with depth.

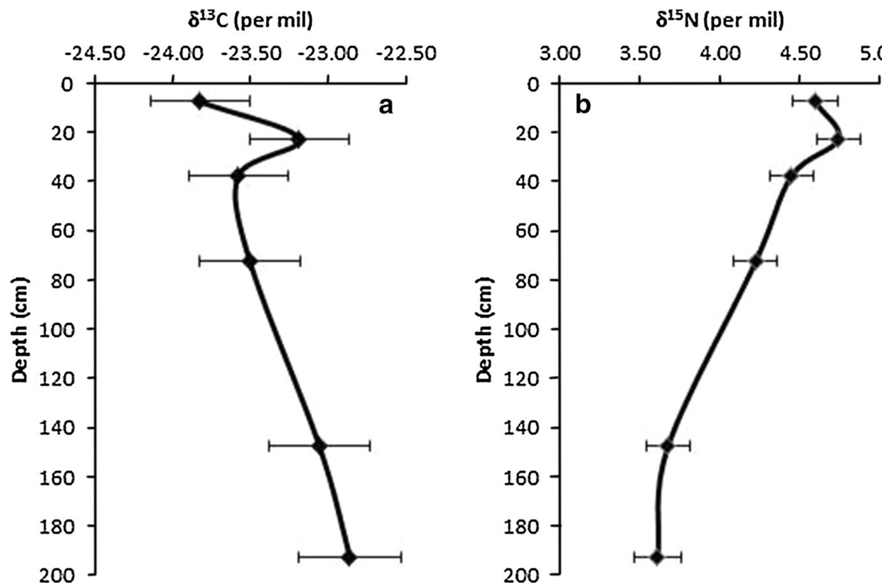

Fig. 5 Mean (S.E.) isotopic composition with depth

Conversely, Donato et al. (2011) showed that, within the Indo-Pacific region, % C was significantly higher in oceanic sites compared to rsiverine sites. These contradictory findings speak to the heterogeneous nature of mangrove settings at a global, and even regional, scale.

Although many of the differences exhibited with depth and between settings were significant among settings, the variation was small when compared to soil characteristics from other regions. For example, the difference between the largest and smallest bulk density means across the whole study area is only 0.27 g cm^{-3} and the difference between the largest and smallest % C values is only 1 %. In contrast, mangrove soil % C can sometimes exhibit large spatial variation, as was the case in the Dominican Republic, where % C site depth means ranged from 1.62 to 27.11 % C (Kauffman et al. 2014), and Mexico, where means ranged from 1.5 to 35.1 % C (Adame et al. 2013).

The stable isotope values of the soil C and N show that the soil is enriched in δ^{13}C and δ^{15}N relative to literature values of mangrove plant matter and litter (Bouillon et al. 2004; Cifuentes et al. 1996) and is suggestive of a mixture of terrestrial/mangrove-derived and marine organic matter, similar to studies in Kenya (Middelburg et al. 1996) and southeastern Australia (Saintilan et al. 2013). The smallest proportion of mangrove-derived organic matter was found in the seaward fringe setting. The larger influence of the marine fraction in this zone could be reflective of increased connectivity to open water transporting organic matter derived from phytoplankton or sea grasses. Another possibility is that the organic matter deposited in this area is influenced by the palms and grasses existing in the adjacent sandy swaths, both of which are C_4 plants and would have a similar signature to the marine end-member. The non-mangrove fraction of organic matter in the interior sites is likely due to contributions from macroalgae, which was observed as occurring in dense mats on top of the soil throughout the study area. Contributions from both micro- and macroalgae are often an important autochthonous organic matter source in mangroves (Kristensen et al. 2008) and certainly warrant further study in the Zambezi River Delta. The uncertainties inherent to using general literature values, rather than site specific data, to define endmembers, as well as the simplified two-endmember model used, instead of a more sophisticated model with a larger number of potential sources, mean that the relative contributions reported here should be considered only as a broad characterization of the ecosystem.

Both C and N exhibited a generally decreasing trend with depth. The largest differences with depth were in the interior setting where C decreased by 0.82 % C and N decreased by 0.08 % N. Without

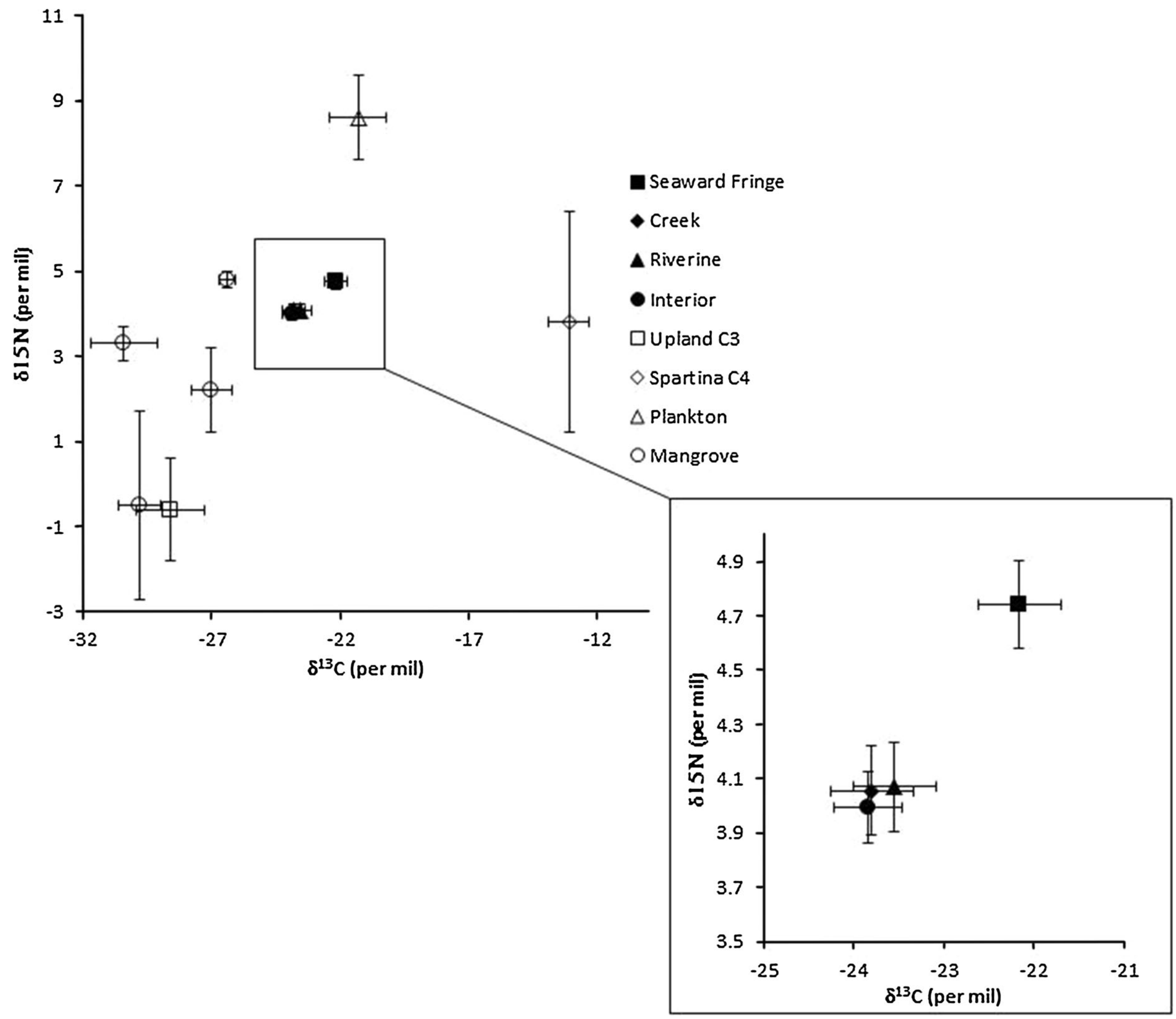

Fig. 6 Mean (S.E.) isotopic composition for each geomorphic setting, plotted with characteristic isotopic signatures for potential organic matter sources in mangrove environments. Source matter values for upland C3, spartina C4, and plankton are from Peterson et al. (1985). Mangrove organic matter data points are from Bouillon et al. (2004) and Cifuentes et al. (1996)

insight into the sedimentation rates in the Delta mangroves, it is difficult to interpret the relationships exhibited in the geochemistry with depth and what that means for organic matter burial. However, the consistent bulk density and C concentrations down to 2 m indicate stable sedimentation conditions.

The Zambezi River Delta mangrove soil characteristics had low variation, despite the large study area (30,267 ha). However, in the broader context of deltaic sedimentary structure, we were investigating only area within the active delta plain, characterized by accretion and functioning distributary channels (Wright 1978). The marshes and swamps that occupy low, flat areas of the active delta plain are generally characterized by high rates of organic matter production and cycling and exist on deposits that are typically structureless (Wright 1978), both of which describe the Zambezi Delta mangroves. Mangrove ecosystems in other large-scale geomorphic settings (delta-lagoon, lagoon, and estuary) may exhibit different levels of variability in their soil characteristics.

It has been well-established that mangroves are carbon-rich ecosystems and that the soil is the largest C pool within that biome (Alongi 2014). Evaluation of the variability of the C content in these systems is inherently needed to fully understand the role of mangrove soil C in the global C cycle. As mangroves

increasingly become evaluated for their sequestration potential for blue C and terrestrial carbon-based programs and markets, soil C spatial variability will provide important insight into the design of high-quality C stock inventories.

Conclusions

This work evaluated the spatial variation in mangrove soil characteristics and examined whether differences could be attributed to differences in geomorphic setting within the larger Zambezi River Deltaic structure. A repeated measures analysis resulted in many statistically significant differences between means with depth and across setting types. However, the variation in characteristics was small when compared to those from other studies. The largest differences in soil character were exhibited between the interior and seaward fringe settings. The low variation shown in measured characteristics corresponds to the structureless nature of the active delta plain within a deltaic setting. Further work is needed to fully examine the spatial variability in other large-scale geomorphic mangrove settings to better understand the role of mangrove ecosystems in the global C cycle.

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