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John F. Machiwa

Distribution and Remineralization of Organic Carbon in Sediments of a Mangrove Stand Partly Contaminated with Sewage Waste

The distribution of soil organic carbon in a mangrove forest partly contaminated with raw sewage shows that a high proportion of the carbon in the landward zones of the forest was organic. Relative content of inorganic carbon increased seawards. Carbonate from the shells of gastropods, oysters, and corals contribute to the inorganic carbon pool. The vertical profiles of organic carbon showed a general surface enrichment and subsurface depletion. An extremely high organic carbon content up to 19% of sediment (dry weight) was found at the sewage dump site. Peat formation was not evident and the organic carbon content decreased with depth of burial in the sediment. The interstitial water at the terrestrial mangrove fringe with sewage waste was relatively more acidic (pH 4–5) and strongly reducing (Eh ~ 300 mV). The pH in the terrestrial fringe that had no sewage influence was close to neutral values (pH > 6). There was no significant difference between the rates of organic matter remineralization in the forest zones. Relative values, however, indicate that mineralization was slowest in sewage-contaminated areas compared to areas without exposure to sewage. The rate of remineralization was high in the frequently inundated mangrove areas.

INTRODUCTION

The knowledge of mangrove systems and their functional ecology has considerably widened in recent years. Commendable investigations have been done and excellent, state-of-the-art reviews on structure and function of mangrove ecosystems have been compiled (e.g. 1). Mangrove sediments and biogeochemical processes therein, however, have not received adequate attention. The distribution and biogeochemistry of organic matter in mangrove sediments is a subject of great interest. As described in Boto (2), tropical mangrove sediments are equated to estuarine and nearshore marine deposits in terms of their broad chemistry and some physical properties. Hesse (3) and Macnae (4) have generalized the mangrove sediments as highly anaerobic, sulfidic muds. However, recent studies (5–8) have shown that mangrove soils are not all extremely anoxic (Eh range from –200 to +100 mV) due to the inherent biotic activities. For instance, presence of crab burrows (9), abundant refractory organic matter (10), and the mangrove breathing roots (11), ensure aeration of the soil. Mangrove breathing roots allow the diffusion of oxygen from roots to the adjacent soil (6, 11, 12), thus creating oxic microenvironments within anoxic sediments. Recently, Tam and Wong (13) have shown that mangrove soils are effective traps for heavy metals. This physicochemical property of mangrove soils most likely suggests the presence of adequate binding sites provided by organic molecules capable of chelation or complexation with the cations. The high binding capacity of mangrove soils also suggests the predominance of clay, capable of adsorption of cations at ion-exchange sites. Generally, the sediment properties vary within mangrove forests depending on tidal regime, and between forests depending on forest type (see references in 1). Large mangroves in deltaic areas have fine-grained substrate, mainly well-sorted silt and clay. They have the highest organic carbon content levels (0.5 to 15% sediment dry weight). Sandy substrates in mangrove forests have the lowest organic carbon levels (0.1 to 0.5%). The amount of organic matter in mangrove soils is determined by *in situ* variables. The major parameters include aboveground biomass, litter fall and litter turnover rates. The sediment organic matter content may be regulated by tidal activity and can be augmented by terrestrial input. The accumulation, burial and slow decomposition of organic matter in mangrove sediments is responsible for the long-term bacterial dissolved organic carbon (DOC) fluxes of these sediments (14). Because the factors that control organic matter input in the mangrove soils are seasonal, in the absence of bioturbation and detritivory, a seasonal trend should be reflected in the sediment column organic carbon levels (15). For example, litter fall and terrestrial organic matter input are seasonal variables.

Sedimentary biochemical processes in mangrove habitats are predominantly anaerobic. Anoxic processes are less efficient in organic matter breakdown, which result in the build-up and evolution of sulfide. Some mangrove soils are, therefore, characteristically black just a few centimeters below the surface due to the hydrotrollite formation, which ages into pyrite. The oxic and suboxic bacterial mediated organic-matter diagenesis may be restricted to the top few centimeters of the sediment. The subsurface production of organic carbon from mangrove roots has been reported by Boto et al. (16). The root-exuded labile DOC in the high and mid-intertidal mangrove sediments colonized by *Rhizophora* sp., can, therefore, be readily available for aerobic microbial degradation (17) which is kinetically favorable and an efficient pathway.

This paper reports the organic carbon content of the sediments of a mangrove stand adjacent to the city of Zanzibar. The specific objective was to determine the effect of sewage dumping on the level and rate of mineralization of organic carbon. It was speculated that peat formation occurs in the soil of the terrestrial mangrove fringe at the sewage dump site. The influence of hydrological, biological and environmental conditions on soil organic carbon content of the mangrove ecosystem was also considered.

STUDY AREA

The sediment of Maruhubi mangrove stand in Zanzibar, East Africa, has been described as sandy or muddy. The landward mangrove soil which is intermittently flooded has the lowest pH and highest level of organic matter (18). The author assumed that the acidity of the soil was caused by the presence of reduced sulfur compounds. Sediments at the marine mangrove fringe had high pH because of frequent inundation. Daily flooding also caused the removal of organic matter from the sediment. Shunula (18) noted that during dry weather, soil salinity in the mangrove forest decreased seaward from the terrestrial mangrove fringe, due to limited freshwater runoff. There is no report on the hydrology and rates of sediment accretion in the mangrove area;

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indeed, the chemistry of these sediments has received little attention. For this study the mangrove forest was divided into subecological zones (19). The marine (MF) and terrestrial (TF) fringe zones are areas with almost monospecific stands of *Sonneratia alba* and *Avicennia marina*, respectively. The areas with mixed species are the shoreline (SL), with *S. alba* and *A. marina*, and the landward extending (LE), mainly with *A. marina* and *Ceriops tagal* (Fig.1). The TF zone was subdivided into two parts, the area which was used for sewage disposal (TFs) and the area without sewage exposure (TFns). The northern part of the forest was used for sewage dumping for about 10 years up to March, 1995.

MATERIALS AND METHODS

Determination of Soil Physicochemical Conditions

Physicochemical factors were determined in the field by inserting appropriate electrodes in the surface sediment. Soil pH and redox potential were checked with glass and platinum electrodes, respectively. Porewater was withdrawn from small holes dug in the soil during low tide, and interstitial water salinity was measured with a hand-held refractometer.

Estimation of Forest Productivity and Rate of Mineralization of Organic Matter

Forest productivity was estimated in terms of litter fall; a detailed sampling protocol has been described elsewhere (18). To estimate the rate of organic carbon degradation in the mangrove soil, samples were incubated in perforated PVC tubes (10-cm long, 2- cm diameter), lined with 80 μm mesh screen. The sediment sample for incubation was prepared by taking mangrove soil from the terrestrial fringe zone, it was wet sieved (125 μm mesh size), then freeze dried. The freeze dried sediment was thoroughly mixed with dry, carbonate-free sand of grain size between 125 μm and 500 μm. The mixture was well homogenized, which improved the porosity of the mangrove fine sediment, and then packed into PVC tubes for incubation. The initial organic carbon content of the incubated samples and the controls was 2.847 ± 0.009% (mean ± SD) dry weight (dw). The sediment samples were incubated at locations MFX, SLX, LEX, TFX (TFns area) and TFX1 (TFs area), representing the main subecological zones of the forest or areas of environmental interest (Fig. 1). Incubated samples were collected from the first to the fourth month of incubation. After incubation, the sediment samples were washed, freeze dried, and homogenized. The samples were used for total organic carbon (TOC) analysis on a Shimadzu TOC analyzer with a solid sample module (SSM - 5000A).

Sampling of Short Sediment Cores

Short sediment cores were retrieved from the forest subecological zones using a hand-held plexiglass pipe (70-cm long, 6 cm diameter). Figure 1 shows the coring locations in the northern, central and southern areas of the marine fringe (MFN, MFC and MFS); shoreline (SLN, SLC and SLS); landward extending (LEN, LEC and LES); and the terrestrial fringe (TFN, TFC and TFS). A total of 16 cores were collected, however, the cores do not fully represent the highly heterogenous sediments of Maruhubi forest. A fresh core was returned to the laboratory, extruded and sectioned at 5-cm intervals. The sediment slices were wet sieved over a stainless steel 125 μm sieve, the fine grain (< 125 μm) was retained for TOC and carbonate carbon (IC) analysis. Fine fraction of mangrove sediment was used in order to allow easy comparison of carbon content in the forest zones. The fine sediment subsamples were freeze dried, then homogenized in agate mortar. The samples were analyzed for total carbon (TC) on a

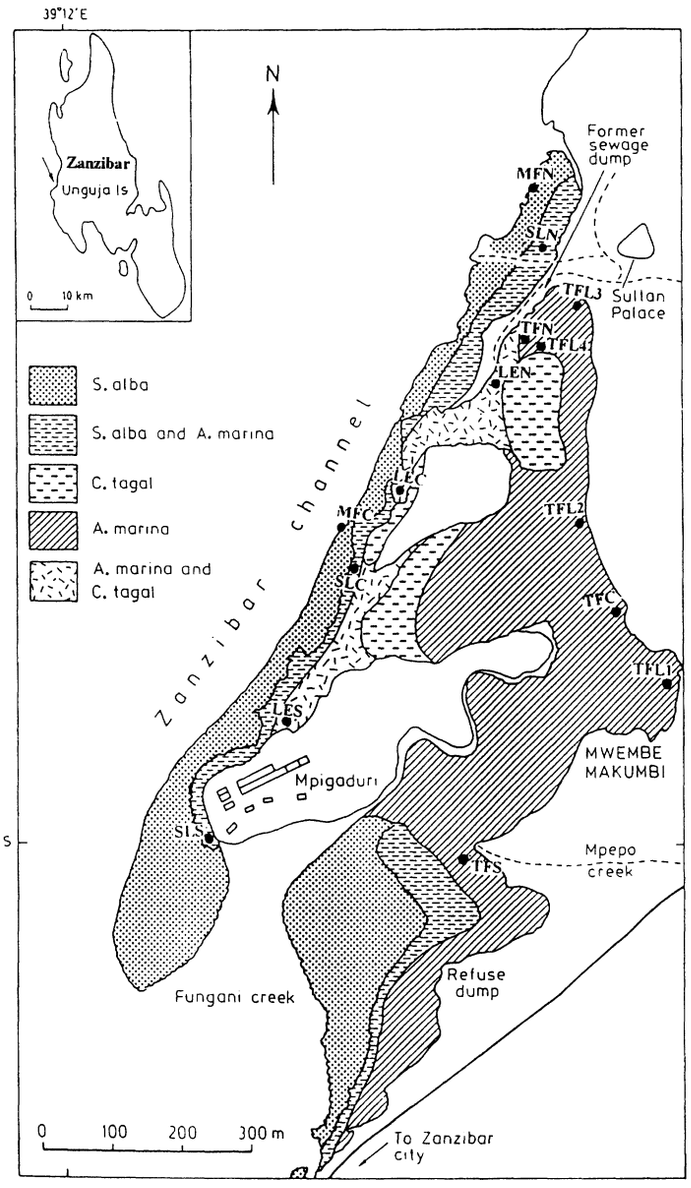


Figure 1. Location map for Maruhubi mangrove area, showing the stations for sampling the sediment cores and incubation of the experimental sediment in the forest zones.

Shimadzu TOC analyzer with a solid sample module. The precision (CV) of sediment analysis was better than 1%.

Sampling of Long Sediment Cores

A 1-meter sediment column was sampled using a hand-operated drill. Portions of 50 cm of the sediment column were taken twice in the same hole. Duplicate cores were taken at each of the stations TFL1, TFL2, TFL3 and TFL4. The first 2 stations are without sewage exposure, and the last 2 are in the sewage-contaminated area. Sediment sections (5 cm) of the long core were freeze dried, and sieved over a 2 mm sieve to exclude large particles of sand and plant debris. Each subsample was homogenized, and analyzed for TOC.

RESULTS

Forest Productivity and Edaphic Conditions

Litter production and litter standing crop data are summarized in Table 1. Litter fall was highest in the TF zone. There was a significant difference ($P < 0.05$) in the rate of litter production among the four main ecological zones. Litter standing crop was lowest in the MF zone; the order of decrease in litter standing

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stock was LE>SL>TF>MF. Litter abundance in the 4 zones of the forest was significantly different ($P < 0.01$). Some physicochemical parameters were also significantly different ($P < 0.05$) in the mangrove forest zones. For instance, soil salinity and organic carbon content increased landwards, while carbonate content increased seawards. However, soil pH was not always significantly different. Redox potential was higher in the sandy substrate of the SL and MF zones, lowest in the sewage contaminated TFs sediments. The MF and SL zones were flooded during all high tides (100% inundation frequency), the LE was inundated by about 50% of the total annual tides, while the TF was flooded by approximately 25% of the tides.

Table 1. Physicochemical and litter data of Maruhubi mangrove forest, values indicate mean (± SD).

	MF	S L	LE	TF
Inundation frequency (% total annual high tides)	100	100	58	23
Soil salinity (ppt)	36.8 (2.5)	36.3 (1.6)	39.4 (2.8)	44.4 (12.0)
Soil pH	6.08 (0.37)	5.46 (0.33)	5.16 (0.43)	5.15 (0.84)
Soil redox potential (mV)range	−114 to +116	−165 to +62	–	−235 to +43
Fine soil organic carbon (%)	2.59 (0.50)	5.86 (3.82)	10.21 (2.44)	8.43 (7.53)
Fine soil carbonate content (%)	1.13 (0.28)	0.07 (0.09)	0.04 (0.10)	0.02 (0.04)
Litter production (g dw m^{-2} d^{-1})	1.7 (1.1)	1.6 (0.9)	0.8 (0.7)	2.2 (1.3)
Litter standing stock (g dw m^{-2})	3.0 (1.7)	8.2 (6.3)	20.4 (14.8)	7.4 (5.2)

Table 2. Monthly decrease of organic carbon content (mean ± SD % dry weight) of the incubated sediment in the forest zones.

Incubation period (months)	Amount of organic carbon in the incubation tubes				
	MF	S L	LE	TFs	TFns
0	2.847 ± 0.001	2.847 ± 0.001	2.847 ± 0.001	2.847 ± 0.001	2.847 ± 0.001
1	2.806 ± 0.004	2.817 ± 0.007	2.795 ± 0.006	2.762 ± 0.003	–
2	2.634 ± 0.006	2.750 ± 0.002	2.652 ± 0.004	2.687 ± 0.006	2.693 ± 0.009
3	2.581 ± 0.003	2.582 ± 0.019	2.605 ± 0.001	2.666 ± 0.006	2.604 ± 0.007
4	2.481 ± 0.005	2.367 ± 0.009	2.579 ± 0.009	2.609 ± 0.004	2.569 ± 0.008

Table 3. Organic carbon content of the fine sediment (< 125 μm grain size fraction) in the forest ecological zones, values are mean (± SD) % dw.

Depth in the sediment (cm)	MF	S L	LE	TF
0–5	2.96 (0.34)	5.97 (4.59)	10.57 (2.94)	8.43 (7.61)
5–10	2.23 (0.31)	5.86 (3.82)	9.83 (2.43)	8.44 (9.16)
10–15	2.48 (0.56)	5.41 (4.20)	8.26 (2.35)	7.74 (7.52)
15–20	2.65 (0.58)	5.81 (4.34)	7.98 (3.75)	7.18 (7.06)
20–25	2.50 (0.49)	5.74 (4.03)	7.55 (3.37)	7.50 (8.12)
25–30	2.10 (0.29)	5.22 (3.85)	–	6.79 (6.85)
30–35	–	–	–	6.68 (5.59)
35–40	–	–	–	7.25 (6.84)

Table 4. Carbonate carbon content of the fine sediment (< 125 μm grain size fraction) in the forest ecological zones, values are mean(± SD) % dw.

Depth in the sediment (cm)	MF	S L	LE	TF
0–5	1.05 (0.33)	0.11 (0.11)	0.03 (0.01)	0.03 (0.06)
5–10	1.21 (0.25)	0.08 (0.14)	< 0.005	0.04 (0.06)
10–15	1.03 (0.43)	0.03 (0.05)	< 0.005	0.02 (0.03)
15–20	1.08 (0.30)	< 0.005	< 0.005	0.02 (0.03)
20–25	1.30 (0.18)	< 0.005	< 0.005	0.01 (0.02)
25–30	1.61 (0.36)	< 0.005	–	< 0.005
30–35	–	–	–	< 0.005
35–40	–	–	–	< 0.005

Decomposition of Organic Carbon in the Fine Grain Deposits

Rates of organic carbon mineralization were compared among the forest zones using the fine sediment fraction. The decrease of organic carbon of the experimental sediment in the PVC tubes was correlated ($r > -0.9$) with the duration of incubation (Table 2). The rate of mineralization was calculated from the slopes of the curves as percentage annual loss of organic carbon with respect to the control. The rates of mineralization of organic matter in the mangrove zones were not significantly different, however, the absolute values show that remineralization was faster at the SL, and slowest at TFs location. Annual rate of removal of organic carbon at the shoreline was 4.2% of the initial amount, at the marine fringe it was 3.4%, at the landward zone 2.6%, at TFns 2.5% and at TFs 2.0%.

Vertical Distribution of Organic Carbon in Mangrove Sediment

The organic carbon content of the < 125 μm fraction of the sediments was highest in the landward and terrestrial fringe zones of the northern part of the forest. These zones had the lowest carbonate content in the fine fraction of the sediment. The SL and MF zones of the northern part of the forest had relatively lower levels organic carbon and higher carbonate content (Tables 3 and 4). Areas without exposure to sewage showed a surface enrichment of organic carbon, the concentration decreased gradually in the sediment column. In the central and southern parts of the forest, organic carbon was highest in areas with higher litter standing crop. The tidal regime favored the accumulation of mangrove, seaweed and seagrass litter in the intermittently inundated LE zone. The disposal of sewage waste in the northern part of the forest significantly increased the organic carbon content of the sediment (Table 3). The organic carbon concentration in the sediments that were contaminated with sewage (TFs) was as high as 17.2% in the surface 5 cm. In contrast, the TFns zone had soil organic carbon content less than 5% in the surface sediment (Table 3). Soil organic carbon content progressively decreased seaward, reaching 12.9% in the LE, 9.9% in the SL, and 3.1% in the MF zone. In other areas of the SL that are not contaminated with sewage, the organic carbon level was low (< 1%). There was a significant difference ($P < 0.05$) in concentration of soil organic carbon in the ecological zones of the forest. The difference in the soil carbonate content in the four ecological zones was also significant ($P < 0.05$).

Organic Carbon Content of the Long Terrestrial Fringe Cores

The vertical distribution of organic carbon in bulk sediment subsamples of 1-meter long cores from the TFns zone (TFL1 area) generally showed a decrease in concentration from surface to bottom (Fig. 2). At TFL2 area, the cores exhibited a subsurface (15–50 cm depth interval) enrichment of organic carbon. However, if this organic rich layer, presumably of anthropogenic

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origin is disregarded, the organic carbon decreases linearly with depth. The cores from the TFs zone (TFL3 and TFL4) had uniformly high organic carbon content in the upper 50 cm, the deeper sediment layers (> 50 cm), had lower organic carbon content. The low concentration of organic matter in the deeper horizons of the TFs sediments, possibly reflects the pre-dumping background level.

DISCUSSION

Remineralization of Organic Carbon in Mangrove Sediments

The preliminary results of organic matter decomposition indicate that mineralization rates in the fine sediment are not significantly different in the zones of the mangrove forest. Nevertheless, absolute values show that the rate can be high in the frequently inundated zones of the forest compared with the intermittently flooded landward areas. The MF and SL zones have sandy substrate, while sediments from the LE and TF zones are muddy or contain fine sand. According to Cammen (20), bacterial abundance is higher in coarse than in fine sediment. Physicochemical parameters such as soil salinity, pH, and redox potential are related to the rate of organic carbon mineralization.The slowest rate of mineralization was at the TFs area, with lowest pH and redox potential values, but highest amount of soil salinity. Organic matter mineralization rate was also related to the quality and amount of soil organic carbon in the forest zones. The objective of the experiment was to consider the influence of environmental factors on the rate of decomposition of organic matter. The fine sediment fraction was used to allow easy comparison between the forest zones and to reduce variability in the lability, type, and quantity of organic matter in the incubated samples. This experimental approach, however, precludes comparison with literature studies in a simple way because previous data is mainly based on fresh mangrove litter (18). Litter particles are discriminated by a 125 µm sieve, the remaining organic carbon fraction is strongly sorbed to the surface of clay and silt particles. The particle-bound organic film is not easily attacked by bacteria, compared to total organic matter. Such a mismatch of the quality of organic matter between the experimental sediment and the true mangrove soil can result in underestimation of the rate of mineralization. Morgan and Hodson (21), however, have reported that in wetland ecosystems the bulk of organic matter in the sediment is in the form of lignocellulose derived from structural material of aquatic macrophytes. The nonstructural material is normally grazed upon by the resident herbivores. In wetland areas, therefore, it is the lignocellulose fraction which mainly undergoes microbial degradation to produce dissolved organic carbon (DOC) and some refractory organic compounds. DOC is used to fuel the energetics of bacteria, but certain types of lignocellulose derived soluble organics are not readily utilized by bacteria, this fraction forms the humic substances. The recalcitrant fraction of lignocellulose derived organic carbon composed of some refractory organics may become associated with the fine sediment. In mangrove ecosystems, the rate of organic matter mineralization is mainly a function of quality and quantity of organic matter on the one hand and on the biological and environmental factors on the other hand. The design of the present experiment explicitly excludes variability of all other factors, hence, any varibility in mineralization rates must be due to environmental conditions.

Distribution of Organic Carbon in Mangrove Sediments

The distribution of organic carbon in the surface soil of the mangrove forest generally shows a seaward decrease in concentration. The vertical profiles indicate a surface enrichment and subsurface depletion of organic carbon in areas that are not affected by sewage wastes. Following disposal of raw sewage, the concentration of soil organic carbon at the dump site increased, however, there is no peat formation in the area. The pH level in the soil of the TFs zone, decreased to low values (pH 3–5), not found anywhere else in the forest. The development of acidity in the soil following sewage dumping can be a result of aerobic mineralization and reoxidation of reduced metabolites such as, NH_4^+, S^{2-}, Fe^{2+} and Mn^{2+}. Nitrification of ammonium and organic nitrogen and oxidation of sulfide is probably the main cause of acidity. Enhanced reoxidation of these soil electron donors as a result of bioturbation, root oxygen release, and long periods of tidal exposure daily, maintain the low pH values. Furthermore, acidity is intensified by the limited buffering capacity of the TFs sediments due to low carbonate content in the soil. Similar low pH values have been reported in soils that were exposed to sewage (22) and high amounts of mangrove organic matter (23). The highest acidity level (pH 2.6) was measured in mangrove soils of Hainan Island (Liao, 1990, cited in 24). The concentration of sewage organic carbon in mangrove soil decreased seawards, mainly because of dilution with sand deposit. Similar results were achieved using a microcosm, which investigated the effect of sewage discharge to mangrove soils and plants (23). The workers reported that soil nutrients and organic carbon content decreased seawards, mostly because of dilution with inorganic deposits. Generally, the level of soil organic carbon at the dump site was of the same order as the organic matter content (20% d.w.) reported at Malacca, a mangrove forest in Malaysia (25). The observed variations in organic carbon in the surface soils in the zones of Maruhubi forest are comparable with results obtained elsewhere; for instance, in the mangrove forests of China and Hong Kong (13, 23, 24), in India (15, 26), in Jamaica (17) and in Australia (10). The authors observed a seaward decrease in sediment organic carbon; the landward stations had consistently high values, in agreement with the present results. These observations are in agreement with Leichtfried's (27) suggestion that the particulate organic matter content of sediment increased with the increasing protection against wind or current. The variation of organic carbon in the forest subecological zones can be attributed to both biological, hydrological and geological factors,

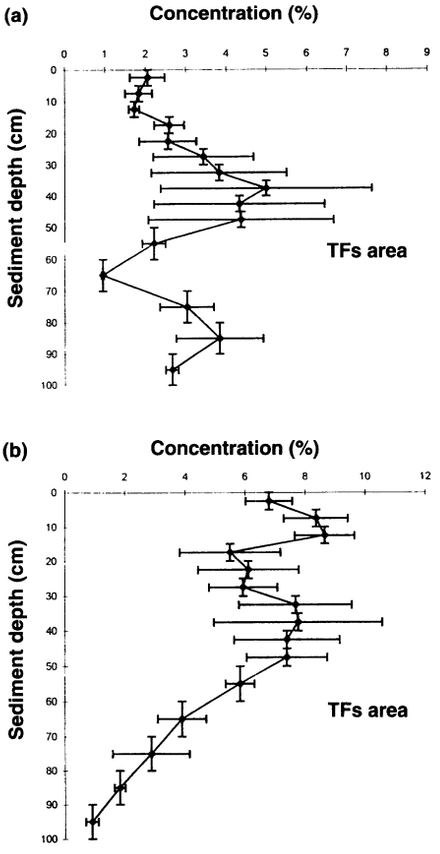


Figure 2. The organic carbon content of the bulk sediment, for the cores from the terrestrial fringe area of the mangrove forest (a) area without sewage; (b) sewage dumping area. Vertical and horizontal bars indicate sampling interval and standard error, respectively.

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on the one hand, and to anthropogenic influence on the other hand. The seaward decrease of mangrove soil organic carbon content, apart from being a result of dilution with sand, is also affected by the frequency of tidal inundation. Variation in the inundation frequency affects tidal export of mangrove litter, litter deposited in the intermittently flooded landward area is mainly retained. Litter production data for Maruhubi mangrove forest suggest that productivity is highest in the TF zone. The soil at the terrestrial mangrove fringe, therefore, should have a correspondingly high organic carbon content. However, due to the high biomass of the resident grazers in the TF zone (19), a high proportion of the soil organic carbon pool, probably, is locked in the burrowing community of grapsid and gecarcinid crabs. In contrast, tidal flow in Maruhubi forest favors accumulation of litter in the SL-LE zone. The LE area has relatively low grapsid crab biomass, it contains the highest soil organic carbon content relative to other areas without sewage exposure. SL and MF zones have high litter-fall rates, but low organic carbon content. The mismatch between soil organic carbon content and rates of litter production is due to daily flooding by tides, which mobilizes litter and probably leaches soil organic matter. The tidal regime of the area imports particulate matter of high carbonate but low organic carbon content, and exports particles of high organic but low carbonate content. This preferential deposition of inorganic material in the MF and SL zones dilutes the sediment organic carbon pool. The sedimentary organic carbon content in the forest, therefore, is a balance between input of organic carbon (mainly litter and sewage) on the one hand, and dilution by inorganic material (e.g. sand) and mineralization on the other. According to the levels of soil organic carbon content, sewage is drained from the TFs area, through the northern and central LE zone to the central part of the SL and MF zones (Table 3). The LE and SL zones of the southern part of the forest have high soil organic carbon content, mainly from an adjacent fish landing station, a major hotel, and a port.

Generally, the temporal variations of organic carbon content down the cores were narrow in the fine sediments, suggesting that the organic matter which is associated with the fine grains is probably refractory, and resistant to bacterial attack. Variations in organic carbon levels in the sediment layers were reported by Jagtap (26) and Sardessai (15) in a mangrove environment in India. Soil organic carbon concentrations in the range of 0.17 to 5.7% (d.w.), were observed. Higher values of soil organic carbon were associated with the onset of the warm rainy weather. The existence of seasonal variations in sedimentary organic carbon can be possible in areas where the mangrove litter is the major source of organic matter. Pristine mangrove environments are rare and in some cases, marine or terrestrial inputs of organic material can be high. Use of fine sediment in the present study, however, precludes comparison in a simple way with values of organic carbon which are normally based on bulk sediment. Sieving essentially normalizes the vertical distribution of soil organic carbon and improves comparison of within forest levels.

Surface samples of the long cores retrieved from the TFns area have the expected normal concentration of organic carbon in the bulk sediment (Fig. 2). The subsurface levels, however, indicate incidents of high input of organic carbon. The elevated concentration of organic carbon in the subsurface soil at TFL2 location indicates previous waste-dumping activity. The remnants of coconut husks in the area suggest earlier dumping events which are not documented. The depositional history of sediment layers at TFL2 area shows severe inconsistencies in the input of organic carbon. Area TFL1 has little or no disturbance from cultural activities, hence, the organic carbon vertical profile indicates decreasing concentration with depth in the sediment. Despite the linear trend, the sediment accretion rate at TFL1 location can not be determined from the vertical profile of organic carbon and rate of mineralization. The rate of organic matter decomposition in the forest is based on fine sediment fraction. The cores from TFL3 and TFL4 areas show that sewage dumping was a continuous operation for the entire duration. The predumping soil organic carbon content indicates that the area was sandy before dumping of raw sewage commenced.

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