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The Role of Hydroperiod, Soil Moisture and Distance from the River Mouth on Soil Organic Matter in Fukido Mangrove Forest, Ishigaki Island, Japan

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Abstract— **Coastal wetlands are experiencing sea level rise, global warming and vegetation shift due to climate change. Climate change may influence soil organic matter mineralization, which plays an important role as a sink for atmospheric carbon; therefore it is important to identify the impact of hydrological processes on soil organic matter. We investigated how soil organic matter content responds to hydroperiod (i.e., the length of time portion of year during which the wetland area is waterlogged), distance from the river mouth and soil moisture content in subtropical Fukido riverine mangrove on Ishigaki Island. The relationships between soil organic matter with the hydroperiod, moisture and distance from the river mouth were analyzed by performing principle component analysis (PCA) on the log-transformed data set and by simple correlations. The organic matter in the sediments ranged between 5.8 and 23.1 %, with an average of 12.3 ± 3.3 % (SD) and decreased from river side to landward side. Our results show that soil organic matter presents strong positive correlations with soil moisture ($r = 0.88$, $p < 0.01$) and hydroperiod ($r = 0.53$, $p < 0.05$) and a strong negative correlation with the oxidation-redox potential ($r = -0.81$, $p < 0.01$). These results revealed that variation in soil inundation and moisture content affect the amount of organic matter in the sediments. Our data support the conclusion that sea level rise, might alter early diagenesis in mangrove sediments, and therefore the fluxes of nutrients in coastal ecosystems and the role of organic matter as a sink for atmospheric carbon.**

Keywords— **Blue carbon, anoxic soil, inundation, sea level rise, decomposition, mineralization**

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I. Introduction

Estuarine regions have received broad attention from researchers because of their importance in transporting high amount of sediment and particulate organic matter from rivers to marine environments [1]. Coral reefs, seagrass beds and mangroves of coastal regions impacted by major rivers are active zones of biogeochemical transformations [2] and form the important store house of sediments and organic matter on Earth [3].

Mangrove forests perform a critical role in maintaining a high biodiversity and provide coastal protection from erosion caused by storm surge and tsunamis [4] [5]. Mangrove forests are threatened globally due to clearing for aquaculture, agriculture, urban and industrial development [6] [7]. Recent researches have highlighted the valuable role of coastal and marine ecosystems in playing sequestering CO_2 [8] [9] [10]. The carbon sequestrated in vegetated coastal ecosystems, specially mangrove forests, seagrass beds, and salt marshes, has been termed "blue carbon". Among terrestrial ecosystems, mangroves are one of the most productive ecosystems, containing on average 1,023 Mg carbon per hectare [10] [11] [12] [13] [14]. Organic matter is highly concentrated in the soils and sediments of coastal wetlands [8] [9] [10] [14]. The mineralization of this soil organic matter (SOM) can release large masses of carbon dioxide (CO_2) to the atmosphere and adjacent waters [11] [15]. Because organic matter deposition and mineralization regulates coastal ecosystem material fluxes and productivity, it is important to identify cause of variation in this process. These causes of variation include soil inundation (hydroperiod) and water content (soil moisture), temperature, and plant species composition, which are themselves sensitive to climate change. Coastal wetland soils often exhibit negative redox potential [16] [17], particularly during prolonged hydroperiod [18] [19].

Hydroperiod has been largely overlooked in studies of the spatial distribution of soil organic matter. The hydroperiod is the length of time portion of year during which the wetland area is waterlogged and is determined by ground elevation, tidal frequency and amplitude. Global climate change possibly increases hydroperiod and soil moisture content owing to sea level rise. We therefore investigated how soil organic matter content correlates to hydroperiod, distance from the river mouth and soil moisture content in subtropical Fukido riverine mangrove on Ishigaki Island.

II. Materials and Methods

A. *Study area*

The study was conducted in Fukido River estuary mangrove forest, located in the northeastern part of Ishigaki Island, southwest of Ryukyu Islands, Japan (24^{o} 30' N and 124^{o} 25' E) facing East China Sea (Fig. 1). The Fukido River estuary has been also designated as a national sanctuary by the Ministry of the Environment of Japan. The mangrove *Rhizophora stylosa* Griff., and *Bruguiera gymnorhiza* (L.) Lamk., is the dominant species at the study site. However, a few patches of *Excoecaria agallocha* L. have also been observed. Mangrove forests comprise approximately 13 ha of the estuarine areas. The catchment area of the Fukido river basin is about 3.3 km^2. Fukido River basin upstream areas are characterizes by steep mountainous terrain, and broadleaf forests which account for about 78% of the basin area. The rest is divided into several types of agricultural land, such as sugarcane field and orchards. The study site is characterized by karst, a special type of land-scape found on carbonate rocks.

Figure 1 Map of study area. (a) Location of Ishigaki Island. (b) A1, A2, A3, A4 and A5 (Transect 1plots); B1, B2, B3, B4, B5, B6 and B7 (Transect 2 plots); C1, C2, C3, C4 and C5 (Transect 3 plots) and D1, D2, D3, D4, D5, D6 and D7 (Transect 4 plots).

B. *Methodology*

The field survey was conducted from February to September, 2013. We established 4 transects, which comprised of 24 plots (7 m radius) perpendicular to the coastline or the bank of the Fukido River (Fig. 1). We used a simple method for measuring transects topography with a measuring pole and using air pressure as an indication of elevation. But surveying requires greater precision. A variety of means, such as precise leveling (also known as differential leveling), have been developed to do this. With precise leveling, a series of measurements between two points (2 meter interval) along transects were taken using an instrument and a measuring pole. Differentials in height between the measurements are added and subtracted in a series to derive the net difference in elevation between the two endpoints of the series. For each measuring location GPS point was also measured. Figure 2 shows the elevation results along the four transects.

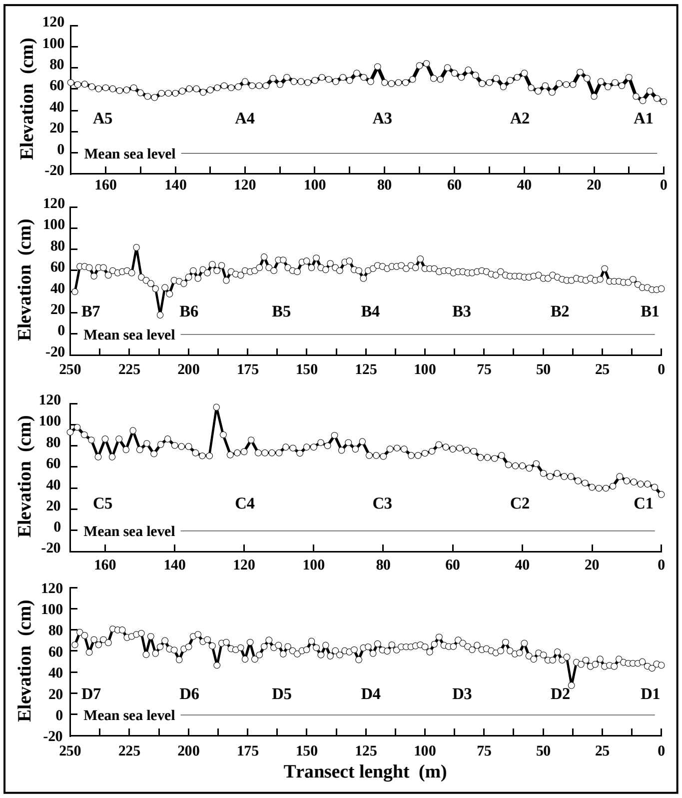

Figure 2 Elevation above the mean sea level along transects and plot location corresponding to elevation.

Hydroperiod was calculated from the elevation above sea level for each plot, derived from topography data collected for each transects during the survey period. A water level logger (HOBO) was deployed at the river mouth during the data collection to record tidal heights. The tide heights for a year were used to incorporate the annual variation in tidal amplitude for the study area. The tide heights data was obtained from Japan Meteorological Agency. We calculated the duration of inundation for each transect, which ranged from 0% (never inundated) to 100% (always inundated), then matched the elevation of each transects to the vertical elevation class and extracted the percentage of time for which each plot is inundated. Horizontal distance between plots and river mouth was calculated using a WorldView-2 image after inputting GPS point of each plot. Samples were collected by inserting PVC cores into the soil to a maximum depth of 50 cm. Twenty four soil cores were collected from the study sites. Each core was sliced in 5 cm layers up to 50 cm depth. Each core section was placed in aluminium foil and kept in ice for transport. In the laboratory, each sample was carefully sieved and homogenized to remove roots and other large plant debris prior to oven-drying to constant weight at 60^{o}C. We then combusted soil in a programmable muffle furnace at 550^{o}C for 5 hours. SOM was calculated as the weight loss at 550^{o}C for 5 hours. Soil moisture content (%) was determined for each soil layer sample by weight loss at 60^{o}C at constant weight. Redox potential was measured in each plot at top 20 cm soil using HORIBA electrode. For each plot 8 redox potential measurements were taken and mean value was used for the analysis. Relationships between the variables (hydroperiod, distance from the river and soil moisture content) among plots were analyzed by performing principle component analysis (PCA) on the transformed data set and by Pearson correlations.

III. Results and Discussion

Table 1 summarises the results of redox potential, distance to river mouth, hydroperiod and soil moisture (mean value of 0-50 cm depth) for each plot of transects. Along transect 1, showed negative redox potential and soil moisture increased from riverward to landward side (Table 1). Transect 2 and 4 showed negative redox potential and higher soil moisture for riverside plots.. Transect 3 showed opposite trends than transect 1 for redox potential. Soil moisture variation trends along the transect 2 and 4 are opposite to that along transect 1. Mean redox potential for transect 1, 2, 3 and 4 were -57.9 ± 13 (SE), -67.6 ± 43, 46.3 ± 30 and 54.8 ± 25 mV respectively. Transect 1 and 2 showed negative redox potential in contrast with transect 3 and 4, which means transect 1and 2 are having anoxic soil condition due to long inundation. The strongly reduced soil is associated with a very high sulphide concentration [17]. Factors inhibiting the build-up of sulfidic conditions include the influence of root and in faunal activities, tides, iron content, and the quantity and quality of organic matter [20].

Hydrology is an important component in an estuarine mangrove ecosystem, because it controls the water level, water residence time, horizontal and vertical hydrological exchange, redox potential and salinity. Along transect 2, 3 and 4 hydroperiod decreased from riverward to landward side except for the plot B6 and C4, which shows higher hydroperiod due to the availability of small creek (Fig. 2). Mean hydroperiod for transect 1, 2, 3 and 4 were 55.0 ± 3.2 (SE), 62.0 ± 4.5, 39.2 ± 10.6 and 55.1 ± 5.3 % respectively. Transect 2 and 4 shows high amount of soil moisture as compared to transect 3, which is correspond to low hydroperiod in transect 3 (Table 1). Mean soil moisture content of transect 1, 2, 3 and 4 were 127.8 ± 22.8 (SE), 108.6 ± 16.7, 38.1 ± 3 and 92.7 ± 12 % respectively. Transect 3 showed the lowest hydroperiod and soil moisture content compared with other transects. Average soil moisture of the study area was 93.3 ± 9.6 %. Soil water content in *Avicennia germinans* mangrove forest in Salt Springs Run tidal estuary in Peninsular West-Central Florida USA ranged from 75 – 85 % of the soil mass [21].

Table 2 shows the variations of SOM contents in soil profile (0 – 50 cm) and spatial pattern along the four transects. The soil organic matter showed a clear spatial pattern. From landward to riverward side in transects 2, 3 and 4, SOM increased. However, transect 1 showed decreasing SOM tendency from landward to riverward side. Along transect 1, SOM changed from 9.66 ± 0.51 to 19.8 ± 0.84 %. In transect 2, SOM value varied from 8.18 ± 0.48 to 18.3 ± 1.5 %, with the highest values in the more riverward sides. Transect 3 showed the lowest value of SOM among all transects, which changed from 7.4 ± 0.9 to 11.6 ± 0.51 %. Along transect 4, SOM values decreased from riverward to landward side with value from 8.0 ± 0.4 to 15.2 ± 0.8 %. The SOM increased with the depth of soil. SOM values for 0-10, 10-20, 20-30, 30-40 and 40-50 cm were 11.9 ± 1.0, 11.6 ± 0.9, 12.1 ± 0.7, 12.8 ± 0.8 and 13.1 ± 0.7 %, respectively. The average SOM concentration for the whole (0-50 cm) soil layer was 13.5 % in transect 1, 13.4 % in transect 2, 9.6 % in transect 3, and 12.2 % in transect 4. Mean SOM in the current study was 12.3 ± 0.3 %. Mean SOM in *Avicennia germinans* mangrove forest in Salt Springs Run tidal estuary in Peninsular West-Central Florida USA showed much higher value, 41.1 %, than the current study [21]. The important outputs of SOM include decomposition, mineralization and erosion, which are influenced by several biotic and abiotic conditions [22].

Table 1 Redox potential, distance to river mouth, hydroperiod, and soil moisture content of twenty four plots in Fukido mangrove forest, Ishigaki Island, Japan

Plot	**Redox potential (mV)**	**Distance (m)**	**Hydroperiod (%)**	**Soil Moisture (%)**
A1	- 33.3	104.1	65.9	88.9
A2	- 69.3	143.6	52.9	75.9
A3	- 29.8	182.8	46.1	112.2
A4	- 101.0	221.0	54.1	168.7
A5	- 56.0	255.8	56.2	193.2
B1	- 37.8	305.1	81.4	141.7
B2	- 197.3	341.5	61.6	136.2
B3	- 203.0	377.8	57.9	152.2
B4	- 158.3	414.5	56.2	95.7
B5	32.3	455.0	49.5	134.6
B6	26.8	492.2	75.3	58.5
B7	63.8	532.3	52.4	41.2
C1	- 48.1	368.3	78.6	45.3
C2	30.8	401.9	39.1	41.6
C3	38.1	435.4	20.9	34.8
C4	77.8	470.6	38.0	41.0
C5	133.0	507.0	19.3	28.0
D1	- 38.1	222.6	78.6	132.4
D2	26.6	253.7	69.8	103.1
D3	- 15.9	288.3	45.4	126.8
D4	76.0	321.9	51.2	67.4
D5	80.5	359.8	48.7	71.1
D6	109.0	393.4	52.9	100.2
D7	145.4	430.0	39.1	48.1

Table 3 showed Pearson correlation analysis results between parameters and SOM with soil depth. SOM showed very strong positive correlation with soil moisture (Table 3). [21] also showed the strong relationship between soil moisture and SOM. SOM did not show significant correlation with river mouth distance (Table 3). On the other hand, SOM showed significantly positive correlation with hydroperiod. As illustrated in Figure 3, the first axis of the PCA explains 77.18

% and the second axis only 11.13% of the total variation between the sites. According to the PCA graph, the SOM of each layer is strongly correlated with the SOM of the precedent layer. The only factor which could explain SOM fluctuations is the soil moisture because the arrow is almost parallel with the SOM at the surface. The other factors, hydroperiod and distance to the water network are strongly negatively correlated with each other (their arrows are at 180° from each other). The distance seems not correlated with the SOM as well as the moisture. The hydroperiod is correlated with the moisture. The PCA here shows also that the collinearity between the SOM of the different layers in the one hand and between the moisture and the SOM at the top layers are strong and confirms the VIF (Variation inflation factor) calculated before.

Table 2 Soil organic matter at different soil depth in twenty four plots on Fukido mangrove forest, Ishigaki Island, Japan

	Soil organic matter (%)				
Plot	***0-10 (cm)***	***10-20 (cm)***	***20-30 (cm)***	***30-40 (cm)***	***40-50 (cm)***
A1	10.1 ± 1.1	11.4 ± 0.7	10.7 ± 0.3	9.7 ± 1.5	10.4 ± 3.3
A2	11.1 ± 3.1	8.8 ± 0.5	8.3± 0.8	9.7 ± 0.4	10.4 ± 0.3
A3	14.8 ± 5.2	13.7 ± 1.9	11.0 ± 1.8	11.0 ± 1.8	9.9 ± 0.7
A4	24.0 ± 4.5	17.8 ± 2.0	13.6 ± 0.4	7.9 ± 0.8	14.4 ± 2.5
A5	18.9 ± 3.2	23.0 ± 4.1	20.1 ± 0.8	18.6 ± 0.8	18.6 ± 1.4
B1	16.6 ± 1.4	14.2 ± 1.9	13.5 ± 0.9	13.1 ± 0.5	12.4 ± 0.7
B2	17.0 ± 1.6	12.2 ± 1.8	11.7 ± 1.3	14.5 ± 0.7	16.4 ± 0.5
B3	17.3 ± 1.8	22.2 ± 3.6	20.2 ± 0.6	18.5 ± 3.2	13.5 ± 2.0
B4	14.0 ± 3.7	11.9 ± 0.4	17.4 ± 4.3	18.1 ± 5.1	15.1 ± 1.4
B5	11.5 ± 0.5	9.9 ± 0.3	13.2 ± 3.1	18.6 ± 3.4	23.1 ± 4.3
B6	8.9 ± 1.1	7.6 ± 0.8	8.6 ± 0.5	9.8 ± 0.9	7.9 ± 0.6
B7	6.9 ± 0.6	7.4 ± 0.6	9.3 ± 0.9	8.1 ± 0.1	9.2 ± 0.1
C1	10.4 ± 1.7	10.6 ± 0.2	13.2 ± 1.3	11.6 + 1.0	12.0 ± 1.7
C2	8.1 ± 0.5	7.3 ± 1.0	8.7 ± 0.4	14.0 ± 1.9	13.5 ± 1.3
C3	6.4 ± 0.5	8.3 ± 0.6	11.2 ± 2.6	9.3 ± 0.2	11.3 ± 0.2
C4	8.2 ± 1.5	8.1 ± 0.3	10.6 ± 1.3	10.3 + 0.7	10.5 ± 0.8
C5	5.8 ± 1.0	6.1 ± 0.5	6.6 ± 0.1	8.0 ± 0.3	10.5 ± 1.0
D1	18.1 ± 2.3	13.0 ± 1.4	12.4 ± 0.5	14.0 ± 1.7	17.0 ± 0.7
D2	12.3 ± 0.9	13.5 ± 0.6	14.7 ± 1.2	19.4 ± 1.5	14.4 ± 0.6
D3	14.1 ± 1.7	13.8 ± 1.1	13.9 ± 0.4	17.5 ± 2.5	16.5 ± 0.6
D4	9.3 ± 0.9	11.6 ±1.0	9.5 ± 0.6	11.3 ± 1.1	12.4 ± 0.9
D5	6.8 ± 0.5	9.1 ± 1.3	13.3 ± 4.5	12.8 ± 0.2	14.2 ± 3.5
D6	6.8 ± 0.7	8.3 ± 0.6	10.6 ± 1.2	13.7 ± 1.4	12.7 ± 0.5
D7	7.0 ± 0.4	7.5 ± 0.2	8.6 ± 1.3	7.8 ± 0.3	9.1 ± 0.8

Higher soil saturation and longer hydroperiod supress carbon mineralization in coastal wetland soil [21]. In Yingluo Bay, SOC concentration and stocks have a similar trend compared to elevation. This indicated a hydrological gradient associated with an increase in soil surface elevation and this hydrologic gradient affected SOC quality and quantity from upstream to downstream along the estuary in this area [23]. Recent study by [24] also confirms that, hydroperiod is the main driver of the spatial pattern of dominance in mangrove communities, which leads to spatial distribution of SOM. Tidal fluctuation and waves would remove the finer fractions of sediments with their higher SOC concentration from seaward zones [25]. In Micronesia, [26] found SOC was significantly correlated with relative elevation ($R = 0.42$; $P = 0.02$), which suggests that hydrologic factors may affect the growth and SOC relationship.

Table 3 Pearson correlation coefficients of the hydroperiod, soil moisture content at different depth, distance to river mouth and soil organic matter at different depth in Fukido mangrove forest, Ishigaki Island, Japan

	Soil depth (cm)	**Hydroperiod (%)**	**Soil moisture (%)**	**Distance (m)**
Soil organic matter (%)	0-10	0.555*	0.862**	- 0.450
	10-20	0.531*	0.880**	- 0.461
	20-30	0.522*	0.873**	-0.388
	30-40	0.522*	0.885**	- 0.331
	40-50	0.481*	0.872**	-0.300

Levels of significances are shown as: *0.05 and **0.01.

The SOM also showed significantly very strong negative correlation with redox potential ($r = -0.81$, $p < 0.01$) (Table 3). It is because organic matter is difficult to be mineralized and decomposed under anaerobic condition [27], and dissolved organic carbon from overlying surface soils can be leached to subsurface water under inundated conditions [28] [29]. Recent study also concluded that increasing soil saturation and inundation supress SOC mineralization from coastal wetland soils [21]. Spatial variability of SOM is also regulated by a variety of factors such as export, import, decomposition and burial of organic matter due to sedimentation, temperature, rainfall, salinity and bioturbation [25].

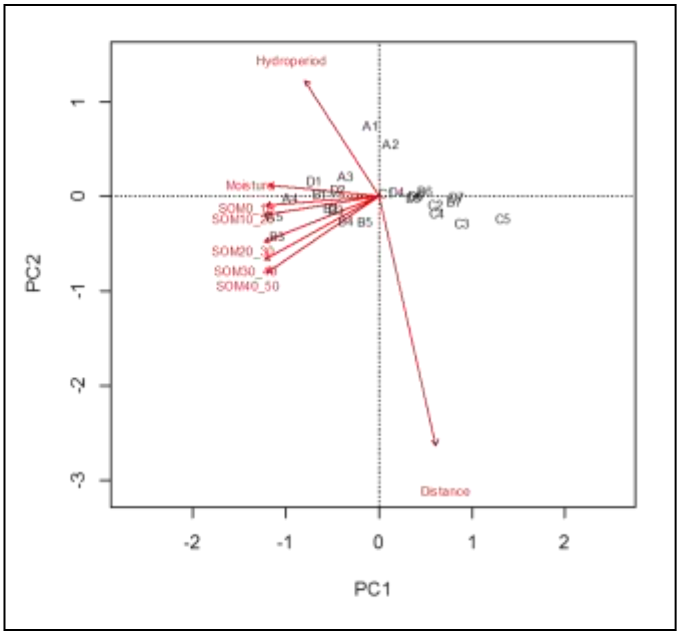

Figure 3 Principal component analyses of variables. A1, A2, A3, A4 and A5 (Transect 1 plot); B1, B2, B3, B4, B5, B6 and B7 (Transect 2 plots); C1, C2, C3, C4 and C5 (Transect 3 plots) and D1, D2, D3, D4, D5, D6 and D7 (Transect 4 plots). PC1 = 77.2%; PC2 = 11.2%.

Our results revealed that variation in hydroperiod and soil moisture content affect the amount of organic matter in the sediments. Prolonged inundation induces negative oxidation-reduction potential, which leads to anoxic soil condition and slower decomposition and mineralization of organic matter in the sediments by microbial communities, thus leading to soils rich in organic matter. Our data support the conclusion that sea level rise, might alter early diagenesis in mangrove sediments, and therefore the fluxes of nutrients in coastal ecosystems and the role of organic matter as a sink for atmospheric carbon.

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