Soil Surface Properties Control the Stabilization of Organic Matter in the Raised-bed Soils of Tidal Swamplands

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Abstract. Stabilization of organic carbon (OC) in raised-bed soils of tidal swamplands reduces greenhouse gas emissions and increases soil OC contents. However, factors controlling OC stabilization in the raised-bed soils of tidal swamplands remain unclear. Relationship between OC contents of bulk raised-bed soils differing ages (2, 8, 15 and 26 years) and soil surface properties was quantified to determine soil properties control OC stabilization in the raised-bed soils. The OC contents were also measured for different soil particle size fractions: clay+silt (0–50 μm), fine sand (50–200 μm), and coarse sand (200–2000 μm). Results of the study showed that the OC contents of bulk soils decreased significantly when the age of raised-bed reached to 26 years. This decrease may attribute to the changes in soil surface properties (clay content, exchangeable Ca, dithionite-extractable Fe, oxalate-extractable Fe and Al, and soil reactivity) with increasing the age of raised-beds. Reduction is OC contents was observed all soil fractions with increasing the age of raised-bed soils. The OC losses after 26 years of cultivation were 83%, 71%, and 11% in the coarse sand, fine sand and the clay+silt fractions, respectively. Results obtained in this study suggest the important role of clay+silt fraction in the long-term accumulation of OC in the raised-bed soils.

1. Introduction

Farmers of tidal swamplands generally divided their lands into two areas; one area was left in flooded condition and planted with rice, while other part of the areas were elevated through the deposition of organic matter that has decayed from surrounding areas and mixed with muddy silt-clay minerals from sunken-beds and then piled them onto the raised-bed [1, 2, 3]. In the raised-beds, the farmers then cultivated horticulture, cassava, fruits and perennial crops [4, 5, 6]. Long period of crop cultivation in the raised-bed soils may lead to a decline in soil quality. Previous study showed that the content of organic carbon and nitrogen in soils decreased significantly with progressing the age of raised-beds [7].

Soil organic carbon (OC) plays a crucial role in controlling soil fertility and land productivity. The contents of OC control the availability of soil nitrogen for plants [8, 9, 10] and the amounts of...
studies emphasize the importance of phosphorous soil absorbed by plants [11, 12, 13], which eventually influence the crop productivity [14, 15]. Results of previous studies showed that the reduction of soluble and toxic Cr(VI) to insoluble and non-toxic Cr(III) in soils increases with increasing the contents of OC in soils [16, 17]. Immobilization of heavy metals in rhizosphere of wetlands is also related to the contents of OC in soils [18, 19] and is influenced by the addition of biofertilizers [20]. Results of these studies emphasize the importance of organic matter for improving soil quality that eventually increasing crop productivity.

Deposition of the mixture of organic matter that has decayed and muddy silt-clay minerals from sunken-beds onto the raised-bed was aimed to elevate raised-bed surface. This process may also improve the stabilization of OC in soils through the interaction between iron and aluminium oxides that may be contained in the silt-clay minerals and OC present in soils. It has been recognized that phyllosilicate clays and oxides of iron and aluminium are the most relevant minerals for OC stabilization in soils [21, 22, 23]. Hydrous oxides of iron and aluminium are capable of interacting with soil OC to develop OC-hydrous oxides association [24, 25], which may be resistant to microbial degradation [26, 27]. The coating of kaolinite with goethite is able to improve the capacity of kaolinite to adsorb OC [28], which is finally increase the stability of kaolinite-OC association against microbial degradation as compared to kaolinite without coating [23]. Results of these study demonstrate that the addition of hydrous iron and aluminium oxide is able to increase in the amounts of protected OC in soils that finally increase the contents for OC in soils. However, information on the factors controlling the stabilization of organic matter in the raised-bed soils is not available. The objective of this study was to quantify the effect of progressing raised-bed soils on organic carbon (OC) contents. Relationship between organic C and physical-chemical soil properties was measured to determine soil characteristics determine the stabilization of organic matter in the raised-bed soils. Bulk soils were fractionated into different fractions: coarse sand (200–2000 μm), fine sand (50–200 μm) and clay+silt (0–50 μm), and then OC contents were quantified for each fraction to assess the effect of fine soil particles on soil OC stabilization.

2. Materials and Methods

2.1. Experimental site and soil sampling

The research site is administratively located in the Desa Karang Indah (3°09'56.6"–3° 10'41.0" S; 114°37'58.3"–114°39'51.4"E), Sub-District of Mandastana, District of Barito Kuala, Province of South Kalimantan. The research site is agricultural lands experiencing a height of about 10 cm from the sea surface which has a tidal effect from the Barito River. The average of monthly precipitation is 222 mm, which is the lowest precipitation of 50 mm (August) to the highest precipitation of 358 mm (February).

Four raised beds experienced different ages: 2 years (made in 2011), 8 years (made in 2005), 15 years (made in 1998) and 26 years (made in 1987) have been selected for this study based on the results of interviews with farmers and field surveys. The field surveys were carried out to ensure that the four raised beds were laid in the same land typology (similar parent materials and the tidal types) and the raised-beds were cultivated with similar crops (orange) and the sunken-beds were used for rice cultivation. The collection of soil samples were conducted a depth of 0-30 cm at several different points. Once cleaned for plant debris, soil samples were then homogenized, stored in plastic bags and stored at 4 °C. The soil samples were then air-dried, sieved and homogenized to 2000 μm for determining soil physical and chemical properties.

2.2. Particle size fractionation

Soil samples were separated into three different particle size fraction using the suspension-sieve method [29]. Briefly, 50 g of air-dried and sieved soil was dispersed in 250 mL of deionized water in 300 container glass on a rotary shaker for 60 minutes. Ten bead glass (3.0 mm diameter) were combined into the container glass to improve the destruction of soil aggregates. Following the dispersion, the soil suspension were fractionated using two connected sieves of 200 μm and 50 μm diameter to obtain coarse sand (200-2000 μm) and fine sand (50-200 μm). The clay+silt fraction was obtained by the...
centrifugation of the soil suspension after sieving of course and fine sands. All particle size fractions were then oven-dried at 60 °C for 72 hours. The fractionation was carried out in triplicate to ensure the precision of method, in which the recovery of soil after dispersion and fractionation was in the range of 976 to 994 g kg⁻¹.

2.3. Soil physical and chemical analysis
Soil physical properties of bulk soils analyzed include clay contents and bulk density [30, 31]. Soil pH was measured at soil:deionized water ratio of 1:5 using the method of glass electrode [32]. Determination of content of organic carbon (OC) of bulk and all fractions of soil was carried out using the Walkley and Black method [33] and nitrogen content of soil was measured using the Kjehdahl method [34]. The cation exchange capacity (CEC) of soils was quantified by the ammonium acetate (pH 7) method [35]. Determination of exchangeable bases (Ca, Mg, Na and K) of bulk soils was conducted by atomic adsorption spectroscopy (AAS) after the extraction of soils with ammonium acetate pH 7.0. The concentrations of Fe and Al in soils were extracted with dithionite (Fe₅⁻ and Al₅⁻) and ammonium oxalates (Alₒ⁻), and then the concentration of Fe and Al in the extract were determined using atomic absorption spectrophotometer. The reactivity of bulk soils was estimated by measurement of changes in solution pOH due to the addition of NaF (ΔpOHₙaf) [36, 37]. Briefly, 2.5 g of soil and 100 ml 0.1 M NaF was shaken for 20 min prior taking the final solution pH. The measurement was conducted in similar soil using deionized water. The ΔpOHₙaf was calculated as a difference in the pOH of soil measured in NaF solution and deionized water.

2.4. Statistical analysis
Analysis of variance was performed on the data of carbon organic and total nitrogen contents to quantify the effect of raised-bed age on organic matter contents. Relationship between soil properties and organic carbon of raised-bed soils was measured using correlation-regression analyses. All statistical analyses were performed using GENSTAT 12th Edition [38].

3. Results and Discussion

3.1. Relation of organic carbon contents and soil properties of bulk soils
Organic carbon contents of bulk soils varied significantly with increasing the age of raised beds, while total nitrogen contents did not affected by the changes in the age of raised bed (Figure 1). Organic carbon contents of the raised-beds with the aging 2 – 15 years were not significantly different (organic carbon contents ranged from 64 to 66 g C kg⁻¹ soil). However, increasing the age of raised-bed soil to 26 years resulted in a significant decrease in the content of organic carbon (56 g C kg⁻¹ soil) (Figure 1).

Figure 1. Contents of total nitrogen (left) and organic carbon (right) of different age of raised bed soils. The vertical bars represent standard deviation (n=3). Similar letters above columns indicate no statistical differences in OC contents between the age of raised bed soils based on the Duncan’ test at P <0.05.
Decreases in soil OC contents with increasing the age of raised bed soils is consistent with the results of previous study [39], who observed that the total OC carbon of soil collected from a mature forestland and from converted forestland to croplands (mainly maize) was 40% less than the original value after 30 years of cultivation. It has also been suggested that the decreased protection of OC in the soils due to disruption of aggregates and multivalent cations leaching may have stimulated mineralization of soil OC and thereby decreasing soil OC contents. Decreases in soil OC contents from the conversion of forestlands to croplands for 100 years were dominated by the losses of light fraction OC and thereby decreasing soil OC contents. Decreases in soil OC contents from the conversion of forestland to croplands (maize) to disruption of aggregates and multivalent cations leaching may have stimulated mineralization of soil OC and thereby decreasing soil OC contents. Decreases in soil OC contents from the conversion of forestlands to croplands for 100 years were dominated by the losses of light fraction OC and thereby decreasing soil OC contents. Decreases in soil OC contents from the conversion of forestland to croplands (maize) to disruption of aggregates and multivalent cations leaching may have stimulated mineralization of soil OC and thereby decreasing soil OC contents. Decreases in soil OC contents from the conversion of forestlands to croplands for 100 years were dominated by the losses of light fraction OC and thereby decreasing soil OC contents.

Table 1. Clay content, bulk density (BD), pH H₂O, ΔpOH NaF, cation exchangeable capacity, dithionite-extractable Fe (Feₒ), oxalate-extractable Fe (Feₒ) and oxalate-extractable Al (Alₒ) of different age raised bed soils.

| Age of raised-bed | Clay content (%) | pH (H₂O) | ΔpOH NaF | CEC (cmol kg⁻¹) | Ca | Mg | Feₒ¹ | Feₒ² | Alₒ³ |
|-------------------|-----------------|----------|----------|-----------------|----|----|------|------|------|
| 26 years          | 65.62 (1.17)*   | 4.82 (0.11) | 3.08 (0.05) | 37.39 (0.68) | 1.72 (0.06) | 0.29 (0.06) | 4.94 (0.40) | 1.59 (0.13) | 0.95 (0.08) |
| 15 years          | 66.42 (1.00)    | 4.19 (0.07) | 3.29 (0.04) | 34.21 (1.65) | 2.79 (0.08) | 0.18 (0.06) | 9.19 (0.10) | 2.91 (0.13) | 1.50 (0.14) |
| 8 years           | 66.64 (0.93)    | 4.09 (0.04) | 3.46 (0.05) | 33.58 (0.86) | 2.66 (0.23) | 0.27 (0.06) | 5.54 (0.49) | 2.29 (0.42) | 1.19 (0.06) |
| 2 years           | 68.43 (1.21)    | 4.38 (0.15) | 4.21 (0.01) | 35.91 (1.49) | 4.28 (0.35) | 0.19 (0.07) | 13.61 (0.23) | 3.64 (0.35) | 2.29 (0.15) |

* Number in parenthesis indicates standard deviation of mean (n=3)

1 Feₒ = dithionite-extractable iron
2 Feₒ = oxalate-extractable iron
3 Alₒ = oxalate-extractable aluminium

Secondary minerals containing hydroxyl groups also play an important role in the stabilization of OC through providing significant surface areas for OC sorption [41, 42]. Oxalate-extractable iron and aluminium (Feₒ and Alₒ) represent extract Al and Fe from poorly-crystalline aluminosilicates, ferrihydrite, and Al- and Fe-humus complexes) and dithionite-extractable iron (Feₒ represents both crystalline and poorly-crystalline Fe oxides, were determined in this study and then correlated with the contents of soil OC. The analysis showed that soil OC contents correlated significantly with Feₒ (r = 0.70; P<0.01), Feₒ (r = 0.80; P<0.01) and Alₒ (r = 0.66; P<0.01), indicating the important role of Fe and Al oxides in the controlling OC contents in the raised-bed soils. The role of Fe and Al oxides in increasing the stabilization of OC also reported in the previous studies. The addition of iron oxide into the soil improves the capability of soil for OC sorption [28], which in turn will increase the stability of mineral-OC association for microbial degradation [21, 26].
Figure 2. Relationship between OC contents of bulk soils and clay contents (a), Δ pOH\textsubscript{NaF} (b), exchangeable Ca (c), dithionite-extractable iron (d), oxalate-extractable iron (e), and oxalate-extractable aluminium (f).

The importance of Fe and Al oxides on soil OC stabilization is also indicated by a significant correlation between soil OC contents with data of F\textsuperscript{−} reactivity (Δ pOH\textsubscript{NaF}). Table 1 showed that raised-bed soils with high OC contents also had high surface reactivity. The high surface reactivity of those soils may due to the high content of the Fe\textsubscript{d}, Fe\textsubscript{o} and Al\textsubscript{o}. Correlation analysis revealed that Δ pOH\textsubscript{NaF} had a significant correlation with Fe\textsubscript{d} (r = 0.86, P <0.01), Fe\textsubscript{o} (r = 0.81, P <0.01) and Al\textsubscript{o} (r = 0.92, P <0.01).

3.2. Organic contents of particle size fraction
The proportion of OC in the soils decreased with the size of fraction (Fig. 3). Mean OC contents were 64.9, 39.0, and 31.8 g C kg\textsuperscript{−1} of fraction in the 0-50, 50-200 and 200-2000 μm particle size fraction. Carbon was lost from all fractions when the age of raised-bed soils increased, although the decline varied from fraction to fraction. The lost from the clay + silt fraction was smaller than from the coarse fractions.
After 26 years of cultivation, the mean losses were 10.7%, 71.1% and 83.5% in the clay + silt, fine sand and coarse sand fractions, respectively.

Figure 3. Contents of OC for 0-50 μm (silt+clay fraction), 50-200 μm (fine sand fraction), and 200-2000 μm (coarse sand fraction). The lines above each bar denote standard deviation of mean (n=3). Different small case litter above the bar show statistically differences in OC contents of raised bed with different ages for each soil fraction based on the least significance difference test at $P<0.05$.

Decreases in OC contents with increasing the age of raised beds were observed for all fractions, which OC associated with fine and has a rapid turnover. Organic C contained in the clay + silt fraction appeared more resistant for microbial degradation compared to those in fine and coarse sand fractions. The findings of this study are attributed to a poor protection of the organic matter from sand-size fractions. Clay + silt fraction protect organic matter either by adsorption of substrates to mineral surfaces [28, 43, 44] or by sequestration in soil aggregates where microbes cannot access OC in the soil aggregates [45, 46]. Results obtained in this study confirmed the role of fine particle-size fraction in the long-term accumulation of organic carbon.

4. Conclusion
Results obtained in this study revealed that content of OC decreased when the age of raised-bed reached 26 years. Soil OC contents in the raised-beds aging $\leq$ 15 years did not change significantly. The contents of OC in the raised-bed soils of tidal swamplands is controlled by surface soil properties such as clay content, exchangeable calcium, and iron and aluminium oxides. Lower OC contents in 26 years raised-bed compared to younger raised-beds ($\leq$ 15 years) due to lower contents of exchangeable Ca$^{2+}$ that function as a bridge between the clay mineral and OC, and decreasing materials that is capable of adsorbing organic carbon such as iron and aluminum oxides.

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