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Soil Structure and Carbon Pools in Response to Common Tropical Agroecosystems

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ABSTRACT

Maintaining soil physical properties and organic C is the goal for sustainable use of soil resources in agroecosystems. The objectives of this research were to evaluate the changes in soil structure and C pools and to quantify the availability of labile C pools. The study site was in Bengkulu Province Sumatra, Indonesia. Four common agroecosystems (fallow field, agroforestry, rubber tree plantation, and grain cropping) were used to determine soil physical properties including bulk density, porosity, and soil aggregates. Labile soil C pools examined were particulate organic C (POC), microbial biomass C (MBC) and C mineralization (C min). Farming practices significantly affected the bulk density, macro-porosity, micro-porosity, aggregate stability (AS), mean weight diameter (MWD) and aggregation ratio (AR). However, the responses from treatments depend upon the soil depth. In general, agroforestry and fallow fields provided lower bulk density, higher porosity, AS, MWD and AR compared to rubber tree plantation and grain cropping. As a general trend, the values of POC, MBC and C min decreased in the order of agroforestry > fallow field > rubber tree plantation > grain cropping. The order of labile C pools in all fields were POC > MBC > C min. Significant increases (32 – 62%, $p<0.05$) in the soil organic C content was observed in agroforestry and fallow fields compared to rubber tree plantation and grain cropping systems at the depth of 0 – 20 cm. The highest available POC (43 to 82%) and MBC (2 to 5%) were found in agroforestry and fallow field. Mineralized C was about 2% in all fields indicating similar amount of active C from soil organic matter. In conclusion, improvement in soil structure properties, TOC, POC and MBC in agroforestry and fallow fields indicated better soil C sequestration and soil quality in these agroecosystems.

Keywords: Aggregation, carbon mineralization, microbial biomass carbon, particulate organic carbon, rubber plantation

INTRODUCTION

Continuous farming with additional fertilizers and tillage practices generally decrease soil quality by disrupting soil structure, depleting soil organic matter and reducing biological activity (Staben *et al.* 1997). These impacts are worse in the tropical areas than in temperate areas (Handayani 2004). Typical farming systems, such as agroforestry and fallows, have been shown to improve soil quality. Plant diversity and biomass are thought to be factors that cause better soil quality.

Farming practices that involve various soil management techniques are known to alter soil properties (Jinbo *et al.* 2007). Previous studies indicated farming practices in the tropics lead to substantial changes in organic matter inputs (Li *et al*. 2009; Handayani *et al*. 2012), thus affected soil C pool dynamics and physical characteristics of the soil. Tillage practices and mulch management influenced the ratio of fungi and bacteria population, enzyme activities and biomass C and N, soil moisture content, bulk density, porosity, compaction, soil fertility and structure (Saviozzi *et al.* 2002; Eynard *et al.* 2006).

The use of manure and commercial fertilizers may affect the organic matter accumulation and lost (Eynard *et al.* 2006). Plowing disturbed soil aggregates by increasing soil pores and enhancing oxidation of soil organic matter that decreased the aggregate stability (Wander and Bidart 2000; Su *et al.* 2009). Deforestation reduced soil organic C content due to enhanced decomposition of organic matter, releasing more CO_2 to the atmosphere.

Fallowing (abandoned land) is one of the common farming practices in the tropical areas in addition to agroforestry, rubber tree plantation and grain cropping. Several benefits of fallowing are to give a rest to the soil, to let the soil having various plants aboveground and to restore the soil nutrients by eliminating cultivation in the soil. The land is usually abandoned temporarily for several years or until some plant indicators for better soil are growing (Templer *et al.* 2005; McLauchan *et al.* 2006). During fallowing, there would be some changes in vegetation cover, physical environment, biological and chemical properties (Jinbo *et al.* 2007; Preger *et al.* 2010; Zhang *et al.* 2010). As a result of these changes, there may be a change in the magnitude of soil physical characteristics such as soil structure, soil water and aeration which finally, will modify how aggregates protect the C. However, the mechanisms related to this phenomenon are not yet clear.

Agroforestry systems improved soil structure and increased soil C sequestration compared to crop fields (Sharrow and Ismail 2004). Soil compaction and less aeration were found in corn-soybean tillage systems than in no-till systems. Decreasing C contents in cultivated fields are due to low aggregate stability and macroaggregates (Puget *et al.* 2000). Lopez-Bermudez *et al.* (1996) reported that fallowing soil for about 7 years showed a significant recovery in vegetation cover and progressive increase in water holding capacity, aggregate stability, saturated hydraulic conductivity, and organic C in the hilly areas of southern Spain. Castro *et al.* (2010) found that litter decomposition tends to be faster as trees are more dominant than shrubs.

Tropical mineral soils generally have low soil organic C content, but about 75% of terrestrial C is found in the soil. Therefore, the contribution of tropical ecosystems become significant in term of soil C storage. Overall, the soils contain about 1550 Pg of soil organic C and 750 Pg of soil inorganic C (Batjes 1996).

Various farming practices have been shown changing the magnitude of soil C, yet few studies document the levels of soil C linked to the physical property changes in typical tropical agricultural ecosystems. These changes need to be evaluated to see the effectiveness of agroforestry, plantation, grain cropping and fallow systems to improve soil quality.

The objectives of this study were (1) to evaluate the impact of farming management systems in Sumatra, Indonesia on soil physical properties and C pools and (2) to quantify the availability of the labile C pools. Particular focus was given to the contribution of agroforestry and fallow systems to improve soils. Documenting such soil changes indicates the direction and magnitude of change associated with altering farming management systems.

MATERIALS AND METHODS

Study Site

The study is located in Bengkulu Province (03°48'S and 102°16'E), Sumatra, Indonesia. The climate is B1 (7 – 9 months wet season and less than two months dry season) according to Koppen's classification, with an annual rainfall between 1,500 – 2,800 mm. Bengkulu had warm tropical climate wet and dry season lasting six month. The wet season was from October to March and the dry season from April to September. The temperature average was 26°C to 32°C. Soil at the study sites was Typic Paleudult according to US Soil Taxonomy, containing 40 – 76% of clay, 22 – 28% of sand, 10 – 28% of silt, and 5 – 24% base saturation, P-Bray 2 – 4.2 ppm, K_2O of 55 – 229 ppm, cation exchange capacity of 15.70 – 28.50 $\text{cmol}_c\,\text{kg}^{-1}$ and pH in water of 4.3 – 4.7.

History of Plantation

Four adjacent farms, agroforestry, rubber tree plantation and grain crop fields had been under cultivation for 30 years and the fallows were less than 10 years. The four agroecosystems were located at *Taman Hutan Raya Rajo Lelo*. Predominant trees in the agroforestry were *Ficus septica*, *Ficus ampelas*, *Ficus variegate*, *Acacia nilotica*, *Cocos nucifera*, *Durio zibethinus*, and *Hibiscus* spp. Fallow fields were dominantly covered by *Wedelia trilobata* and *Chromolaena odorata*. Grain crops were corn and soybean in rotation.

Sample Collection and Analysis

Soil samples were collected from agroforestry, rubber tree plantation, grain crop field and fallow field at the depth of 0 – 10 cm and 10 – 20 cm. Five replicates of soil samples from each depth from four different locations within a farm were obtained. The sampling locations within a land use were at least 25 m to 40 m from each other. The five replicate samples at each sampling location within a farm were combined for each depth. Soil texture, bulk density, porosity, macroporosity, microporosity, aggregate stability and mean weighted diameter of aggregate were determined according to the procedures of Klute (1986). The amount of macro-aggregates was calculated as the combination of all size fractions (4 – 0.25 mm) after wet sieving. Micro-aggregates were defined as <0.25 mm size fractions. The aggregate ratio (AR) was calculated as (Baker *et al.* 2004):

AR = Macro-aggregates (%) / Micro-aggregates (%)

Soil organic C was measured using loss on ignition method. Carbon mineralization (C min) was performed at constant humidity and temperature for 7 weeks following the method by Anderson (1982). Soil microbial biomass C (MBC) was estimated by the chloroform-fumigation incubation method (Jenkinson and Ladd 1981).

Particulate organic C was analyzed according to the procedures of Cambardella and Elliot (1992). A 15-g air dry soil samples were dispersed with 150 ml of 5 g L^{-1} sodium hexametaphosphate and shaken for 18 hours on reciprocal shaker. The dispersed soil samples were passed through a 53 - µm sieve and rinsed thoroughly with water until the rinse was clear. The material retained on the sieves was backwashed into small aluminum pans and dried at 70^{o}C for 48 hours. The longer time was needed to evaporate the water accumulated during rinsing. The dried fraction samples were ground in a ball mill to pass through a 0.25 mm and then analyzed for carbon using muffle furnace.

Statistical Analysis

The data was statistically analyzed using Univariate Analysis of Variance with randomized complete block design (SAS Institute 2007). The main effects were agroecosystems or farming systems (agroforestry, rubber tree plantation, grain crop field, and fallow field) and soil depth (0 to 10 cm and 10 to 20 cm). Least Significant Difference test (LSD test) was used to determine differences between means.

Statistical analyses were based on the assumption that the sites were similar when originally under forest. There were replicate measurements for each agroecosystem, however they were not true replication (*pseudoreplication*), since only one contiguous area represented each farm. This is a common case when working with existing field studies. To justify the above assumption, soil texture, which is not expected to change due to farming practices, was evaluated. Results indicated no significant difference among sites or depths (Table 1).

Table 1. Clay and silt contents in four different agroecosystems and soil depth at study location in Bengkulu Province, Sumatra.

Agroecosystem	Clay (g kg^{-1})	Silt (g kg^{-1})
Agroforestry (AG)	292.05 a	388.12 a
Rubber plantation (RP)	274.21 a	302.22 a
Grain cropping (GC)	262.22 a	341.16 a
Fallow field (FF)	257.32 a	322.63 a
Soil depth		
0 to 10 cm	250.25 a	355.71 a
10 to 20 cm	270.63 a	402.27 a

Similar letter at the same column of agroecosystem and soil depth indicates no significant different at á 5%.

RESULTS AND DISCUSSION

The Effects of Agroecosystems on Soil Physical Properties

Bulk density is closely related to soil compaction. Compacted soils can inhibit the plant growth and slow water infiltration. Soil porosity is a fundamental property affecting many soil water processes (Huang *et al.* 2002). Macropore channel relates to water holding capacity and water infiltration. Micropore channel dominates the flow between aggregates (Luxmoore 1981). Soil aggregation as indicated by wet aggregate stability, mean weight diameter (MWD) and aggregate ratio (AR) is an important measure of soil erosion potential from water forces. Soils with weak aggregates are generally the most susceptible to water erosion (Skidmore *et al.* 1975).

Results show that agroforestry and fallow field provided lower bulk density, higher macroporosity, aggregate stability, MWD and AR compared to rubber tree plantation and grain cropping. Farming practices significantly altered bulk density of surface soil of 0 to 10 cm (Table 2), but not at the depth 10 to 20 cm. In general, the order of the bulk density in the depth of 0 to 10 cm decreased from GC (grain cropping) – RP (rubber tree plantation) – FF (fallow field) – AG (agroforestry). The surface bulk density soil in GC was relatively high to the levels close to the average of bulk density in the depth of 10 to 20 cm. This resulted in soil macroporosity reductions (Table 2). The farming systems with the highest bulk density exhibited as much as a 50% reduction in macroporosity. Microporosity was not significantly affected by farming systems (Table 2). The annual soil disturbances such as plowing and harrowing caused organic matter depletion, thus resulting in low total porosity.

Aggregate stability was significantly affected by farming systems. At the depth of 0 to 10 cm, the highest aggregate stability was found in AG and FF with differences of 14% and 30% compared to RP and GC, respectively. However, when averaged among the farming systems, there was no significant difference of aggregate stability between soil depths. Rubber trees that have deep roots caused lower aggregate stability and organic C in both depths. Frequent tillage practices in GC caused aggregates

Table 2. Bulk density, macroporosity, microporosity and aggregate stability in four different agroecosystems and soil depth at study location in Bengkulu Province, Sumatra

Soil Depth	Agroecosystem	Bulk Density ($Mg\ m^{-3}$)	Macro Porosity ($m^3\ m^{-3}$)	Micro Porosity ($m^3\ m^{-3}$)	Aggregate Stability (%)
0 to 10 cm	AG	1.25 d	0.32 a	0.28 ab	45 a
	RP	1.42 b	0.22 b	0.31 b	40 b
	GC	1.51 a	0.15 c	0.32 bc	35 c
	FF	1.34 c	0.28 b	0.25 ab	46 a
10 to 20 cm	AG	1.62 a	0.12 c	0.32 c	42 b
	RP	1.58 a	0.08 d	0.38 ab	38 b
	GC	1.53 a	0.09 d	0.31 b	34 c
	FF	1.48 ab	0.07 d	0.35 bc	48 a

Similar letter at the same column indicates no significant different at á 5%. There was a significant effect of agroecosystem × soil depth interaction. AG (agroforest), RP (rubber tree plantation), GC (grain cropping), FF (fallow field).

break down resulting in low aggregate stability and the soil became more sensitive to erosion. Plowing increased soil organic matter mineralization causing C depletion.

Farming practices had a significant effect on the MWD and aggregation at the depth of 0 to 20 cm, being greater in AG and FF followed by RP and GC (Table 3). The aggregation ratios (AR) were significantly influenced by farming practices and soil depth, but no significant interaction of both. Similar to MWD data, the AR tended to increase within the AG and FF and to be smaller in RP and GC at the depth 0 to 20 cm (Table 3). The difference of AR between 0-10 cm and 10 to 20 cm was about 63%. However, the effect of farming practices was clear on the surface soil of 0 to 10 cm.

Table 3. Soil organic carbon, mean weight diameter (MWD), and aggregate ratio (AR) in four different agroecosystems and soil depth at study location in Bengkulu Province, Sumatra.

Agroecosystem	Organic C ($g\ kg^{-1}$)	MWD (mm)	AR
AG	17.52 a	1.85 a	0.615 a
RP	13.22 b	1.48 b	0.354 b
GC	10.81 c	1.38 b	0.211 c
FF	16.45 a	1.72 a	0.645 a
Soil depth			
0 to 10 cm	18.58 a	2.15 a	0.705 a
10 to 20 cm	7.92 b	1.32 b	0.358 b

Similar letter at the same column of agroecosystem and soil depth indicates no significant different at á 5%. There was no significant effect of agroecosystem x soil depth interaction. AG (agroforest), RP (rubber tree plantation), GC (grain cropping), FF (fallow field).

In general, macroaggregates had a similar trend to MWD and AR values. GC had low percentage of macroaggregates (Table 3). In contrast, microaggregates showed a reverse trend with a significant lower proportion in the AG compared to other farmlands. As a whole, AG soils showed a substantial increase (35%) in macroaggregates concomitant with an increase (15%) in microaggregates compared to RP. More macroaggregates than microaggregates in the soils indicates higher aggregate stability.

The Effects of Agroecosystems on the Amount and Availability of Labile Soil C Pools

Soil organic C pools provide information about the potential of stabilization or degradation of the soil resource by different farming systems (Handayani *et al.* 2011). Labile soil C pools such as particulate organic matter C (POC), microbial biomass C (MBC) and C mineralization (C min) have been shown their sensitivity to the changes in land use, thus they are good indicators for monitoring soil quality (Gregorich *et al.* 1994; Handayani *et al.* 2012).

Soil organic C was significantly controlled by farming system in both soil depths (Table 3). Grain cropping system had the lowest soil organic C content. Significant increases (32 to 62%, $p < 0.05$) in the soil organic C content was observed in AG and FF compared to RP and GC at the depth of 0-20 cm, with no significant effect at the depth 10-20 cm. Farming practices significantly affected the soil organic C only at 0-10 cm depth. Greater amounts of soil organic C (57%) were found at 0 – 10 cm compared to 10 – 20 cm.

Average concentrations of POC, MBC and C min all increased in AG and FF at the depth 0-20

Table 3. Soil organic carbon, mean weight diameter (MWD), and aggregate ratio (AR) in four different agroecosystems and soil depth at study location in Bengkulu Province, Sumatra.

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Soil depth			
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Similar letter at the same column of agroecosystem and soil depth indicates no significant different at á 5%. There was no significant effect of agroecosystem x soil depth interaction. AG (agroforest), RP (rubber tree plantation), GC (grain cropping), FF (fallow field).

Table 4. Particulate organic C (POC), microbial biomass C (MBC) and cumulative soil C mineralization (C min) in four different agroecosystems and soil depth at study location in Bengkulu Province, Sumatra.

Agroecosystem	POC (g kg^{-1}soil)	MBC (mg kg^{-1}soil)	C min (mg kg^{-1}soil)
AG	12.58 a	890.98 a	315 a
RP	6.52 b	385.29 a	269 a
GC	4.75 c	252.73 a	258 a
FF	11.52 a	750.27 a	321 a
Soil Depth			
0 to 10 cm	15.27 a	924.52 a	386 a
10 to 30 cm	5.42 b	340.20 a	201 a

Similar letter at the same column of agroecosystem and soil depth indicates no significant different at á 5%. There was no significant effect of agroecosystem x soil depth interaction. AG (agroforest), RP (rubber tree plantation), GC (grain cropping), FF (fallow field).

cm (Table 4). POC concentrations were significantly higher at the depth 0-10 cm. There was no significantly effect of farming practices and soil depth on MBC and C min. In the depth of 0-20 cm, the concentrations of POC in AG were 48% and 62% higher than in RP and GC. In FF, the POC content was 43% and 59% higher than in RP and GC. There was no significant difference in MBC and C min in GC and other fields. However, the values of MBC and C min were higher in AG and FF compared to RP and FF. These values were also higher at the depth 0-10 cm than 10-20 cm (Table 4). As a general trend, the values of POC, MBC and C min decreased in the order of AG > FF > RP > GC, and the order of C pools in all fields were POC > MBC > C min. In this study, variability in MBC and C min was high, resulting no significant different among agroecosystems and between soil depths.

Data in Table 5 shows the ratio of each labile C pools (*i.e.*, POC, MBC and C min) to soil organic C showing the availability of labile C to the ecosystem. The highest available POC (43 to 82%) and MBC (2 to 5%) were found in agroforest and fallow field. Mineralized C was about 2% in all fields indicating similar amount of active C from soil organic matter.

Discussion

The Effects of Agroecosystems on Soil Physical Properties

Various agroecosystems have more impact on soil aggregation than bulk density and porosity. Aggregate stability, MWD and AR in grain cropping were the lowest. In annual cropping systems, tillage might influence the aggregate stability (McLauhan *et al*. 2006; Handayani *et al.* 2012) causing weak soil aggregation and structure. According to Jinbo *et al.* (2007) fallowing agricultural land improved soil physical properties by increasing water table aggregates. Li *et al.* (2009) observed a good recovery of MWD and percentage of soil

Table 5. Effect of four agroecosystems on the availability of particulate organic C (POC), Microbial Biomass C (MBC) and Mineralized C (C min).

Agroecosystem	POC/SOC (%)	MBC/SOC (%)	C min/SOC (%)
AG	73 a	5.14 a	1.79 a
RP	49 b	2.91 b	2.03 a
GC	44 b	2.34 b	2.38 a
FF	70 a	4.56 a	1.95 a
Soil Depth			
0 to 10 cm	82 a	4.98 a	2.07 a
10 to 30 cm	68 a	4.29 a	2.53 a

Similar letter at the same column of agroecosystem and soil depth indicates no significant different at á 5%. There was no significant effect of agroecosystem x soil depth interaction. AG (agroforest), RP (rubber tree plantation), GC (grain cropping), FF (fallow field).

aggregation at the depth of 0 – 30 cm following 4 years of fallowing in China. Previous study by Kosmas *et al.* (2000) in the island of Lesvos showed that in undisturbed condition such as agroforestry and fallow land, the aggregate stability improved during 40-45 years without soil disruption. It seems soil organic C contributes significantly in improving aggregate stability, since other factors such as clay contents were almost similar among the land management practices (McLaughan *et al.* 2006). In the loess area, the water aggregate stability in the soil surface of 0 – 20 cm increased under fallow field due to the increase of total organic C (Zhu *et al.* 2010).

Results show that inclusion of different shrubs in agroforestry and fallow fields changed the dynamics of MWD, AR and aggregation (Table 3). The greater soil aggregation in AG and FF compared to RP and GC indicated the important role of shrubs on aggregate stabilization and formation. The positive impacts of the shrubs on aggregate stability could be attributed to shallow root and root activity and the incorporation of leaf residues. Previous research from adjacent fields indicated that residues of shrubs were rich in labile organic C pools (Handayani *et al.* 2012) which increased soil aggregation and soil organic matter. However, this impact is often transient because the labile C pool is easily decomposed.

The Effects of Agroecosystems on the Amount and Availability of Labile Soil C Pools

The organic C content in a soil depends on the balance between C input rate via organic residues and output rate via microbial decomposition (Houghton and Goodale 2004). These two factors are controlled by land management and the presence of plant residues.

The greater soil organic C in agroforestry and fallow field may partly be attributed to enhanced C inputs to the soil because a large proportion of above and below-ground biomass from vegetation is annually added to the soil. On the other hand, a significant portion of aboveground biomass in rubber tree plantation and grain cropping is harvested or exported outside the fields (Zhu *et al.* 2010; Wang *et al.* 2011).

Higher amounts of macro-aggregate and aggregation (i.e. aggregate stability, MWD and AR) in agroforest and fallow field compared to grain cropping indicate the recovery of the water stable macro-aggregate may have protected the organic matter from mineralization and depletion,thus facilitated the organic C accumulation in the soil (Ahn *et al.* 2009).

Physically protected SOM might foster the formation of soil stable aggregates leading the improvement of soil structure (Shrestha *et al.* 2007). Therefore, consequent losses in physical protection of the soil surface organic C could also be responsible for the decline in soil organic C in grain cropping (Balesdent *et al.* 2000). Most results demonstrated that micro-aggregates offer more effective physical protection than macro-aggregates (Six *et al.* 2002). High stratification of soil organic C may indicate good quality of soil. Although, grain cropping caused decline in soil organic C but since the stratification ratio of all fields > 2, then the soil was considered in a good quality (Table 3). According to Franzluebbers (2002), if the stratification ratio < 2, then the soil is degraded.

POC and MBC are considered labile soil C pools, the C min indicates the microbial activity. These three parameters may affect the organic matter quality and availability controlling nutrient cycling. POC, MBC and C min often respond more quickly to the disturbances by agricultural practices or changes in environmental management than other C pools (Handayani *et al.* 2008; Anderson and Domsch 1990).

Farming practices had a significant influence on POC with no substantial effect on MBC and C min. Increased POC in agroforest and fallow field may indicate a greater C availability and subsequently higher microbial activity. The differences in soil organic C content in grain cropping and agroforest or fallow field might have led to differences in POC. Greater inputs of labile C from root exudates could also be accounted for the higher POC and MBC in agroforest and fallow field relative to grain cropping, where living roots were present and active for 3-6 months. It was likely that C inputs via microbial respiration in agroforest and fallow field with natural vegetation causing the minimal loss of soil organic matter.

Significantly higher availability of POC and MBC in agroforest and fallow field could mainly be attributed to addition of varying quantity of organic matter inputs over the years through litter fall (Yadav *et al.* 2008). They observed significant and positive correlation between microbial biomass and available nutrients and soil organic C. The availability of carbonaceous materials such as sugars, amino acids and organic acids to the soil from decomposing litter fall and decay of roots under the canopy of the trees in agroforestry systems and fallow species in fallow field are important for supplying energy for microbial populations (Bowen and Rovira 1991). Variations in POC and MBC due to different farming management systems was also reported by Mazzarino *et al.* (1993); Bauhus *et al.* (1998); and Handayani (2004).

CONCLUSIONS

This research provides evidence supporting the hypotheses that agroecosystems in tropical areas have important contribution to alter soil structure and labile organic matter pools, especially in the surface of 0 – 10 cm. The results demonstrated a clear picture of how agroforestry and fallowing the land could improve soil quality. Desirable physical soil properties that contribute to greater labile C pools correspond to soils managed under agroforestry and fallow. These agroecosystems could be potential practices for reducing CO_2 concentrations in the atmosphere. Such management practices are vital for long-term productivity and sustainability of soil in tropics, where level of soil biological activity is low due to lower soil organic matter. Our results suggest that management practices to promote greater biomass and reduced soil disturbance will increase soil organic C, aggregate stability, and consequently reduce compaction and create better soil quality. However, more studies are needed to further answer the mechanisms of C sequestration involving the roles of bulk soil, aggregates and particle size.

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