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Carbon sequestration in the soils of aquaculture ponds, crop land, and forest land in southern Ohio, USA

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Abstract Soil samples were collected from four aquaculture ponds (yellow perch culture), a control pond (without aquaculture activities, fallow pond), crop land (under corn), and forest land to estimate the carbon (C) sequestration potential in the Piketon county, Ohio, USA. The averaged total of C was 6.5±2, 8.8±2, 8.53±0.2 and 10.49±1.1 Mg/ha (Mg=10^6g) in <0.25 mm fraction; 15.2±2, 16.0±3, 11.49±0.8 and 17.23±3.4 Mg/ha in micro aggregates (0.25–2.5 mm); and 22.1±3, 26.4±3, 12.16±1.6 and 18.51±4.3 Mg/ha in macro aggregates (>2.5mm), for aquaculture ponds, control ponds, cropland and forest land, respectively. The soil/sediment C pool followed the order of forest>crop land soils>aquaculture pond soils.

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Introduction

Organic carbon (C) in agricultural soils contributes positively to soil fertility, soil tilth, crop production, and overall sustainability of land use (Lal et al. 1997). Soil organic carbon (SOC) up to 1.0-m depth is a large and active pool, containing roughly twice as much C as the atmosphere and 2.5 times as much as biota. The C sequestration is the process of redistribution of C from the atmosphere into other reservoirs with a high mean residence time (MRT). Thus, transfer of atmospheric C into other reservoirs of a longer MRT would reduce the rate of atmospheric C increase thereby partly mitigating the accelerated global warming (Tieszen 2000).

Globally, soils are estimated to contain 1,500 Pg (pentagram) (Pg=10^{15} g) of soil C to a depth of 1 m, approximately twice the amount of C in the atmosphere. Around 160 Pg of organic C are stored in soils of agricultural croplands in the world (Stockmann et al. 2013). Improved management practices (conservation tillage, residue retention, and the use of pasture or fertilizer N application) increased soil C by 0.05–0.15 Mg C/ha/year only in the surface 10 cm of soil in Australian croplands, and also these effects were more pronounced during the first 10 years of implementation of improved management practices (Lam et al. 2013).

The storage of C in aboveground biomass is easily assessed by forest inventories. The rate of soil C sequestration is about 0.3 t C/ha/year but is highly variable (Post and Kwon 2000). Soil C sequestration rates in Swedish forest were on an average 96 kg C/ha/year (−60 to 360 kg C/ha/year) (Gundersen et al. 2009).

Aquaculture ponds sequester as much as 0.21 % of the annual global C emissions of about 10 Pg/year (Pg=10^{15} g) and represent a small sink for C which is an important ancillary benefit in considerations of the global C budget (Boyd et al. 2010). The global potential of C sequestration by forests is high, about 0.4 Pg C/year in forest soils and 1–3 Pg C/year total in forest biomes (Lal 2005). The global potential of C sequestration by crop land soils is about 0.4 to 0.8 Pg C/year (Lal 2004). In addition to advancing global food security, C sequestration by the world soils has the potential to offset fossil fuel emissions by 0.4 to 1.2 Pg of C/year, or 5 to 15 % of the global fossil fuel emissions (Lal 2004).

The rate of SOC sequestration with application of recommended technologies depends on soil texture and structure, rainfall, temperature, farming system, and soil management. Soil structure is often expressed as the degree of stability of aggregates (Six et al. 2004). Any addition of organic substrates to soil improves its structure (Ladd et al. 1977) and stabilizes the SOC pool. Soil attributes such as aggregate type, size, and stability can strongly influence the SOC pool (Six et al. 2000; Eynard et al. 2004). Therefore, the objective of the present study was to compare the SOC pool in the soils of aquaculture pond, crop land, and forest land in relation to different aggregate and particle size fractions.

Materials and methods

The study area comprised of a corn (*Zea mays*) field, forest land, and aquaculture ponds in Piketon, Ohio, USA (longitude 83° 9′ 58.3″ W and latitude 39° 2′ 54.6″). The aquaculture ponds are being managed by the Aquaculture Research Center of The Ohio State University South Centers. The yellow perch (*Perca flavescens*) have been cultivated in these ponds for more than 10 years. These perch ponds have been fertilized by using organic plus inorganic fertilizers. Manures and plant meals (cotton (*Gossipium hirsutum*) seeds, alfalfa (*Medicago sativa*), etc.) have been used as organic fertilizers. Ammonium nitrate (concentration 28 % N) and phosphoric acid were used as inorganic fertilizers. In summer and fall, commercial feeds are applied twice a day for growing fish in these ponds. The age of the ponds is 21 years. The average depths of these ponds ranged between 1.0 and 1.5 m and the area of these ponds was about 0.5 ha. Soil samples were collected from the four aquaculture ponds. A nearby pond which is not used for aquaculture purposes was considered as control pond. Thus, the sediment cores were collected manually at four sampling locations from each of the five ponds using a 5-cm-diameter, 50-cm-long transparent plastic core tube according to the methodology described by Steeby et al. (2004). The sediment accumulation rate was estimated by dividing the sediment depth by the age of the pond. After weighing the wet sediment sample, it was divided into two parts and then dried in two different ways. A measured quantity of a part was dried for 24 h at 105 °C using conventional oven, cooled in a desiccator, and weighed again for dry bulk density estimation. The other part of the sediment samples was air-dried, gently ground, and pulverized to pass a 0.25-mm screen and was kept for the analysis of total C concentration. Soil samples were also collected from 0- to 6-cm depth at three sampling locations for each of the nearby corn and forest fields on the same day on which the sediment samples were collected for the control ponds. After 2 days, the sediment samples were collected from the aquaculture ponds. The undisturbed core samples and auger samples were collected in all locations. In all the cases, the soil samples were placed in clear polythene bags, which were labeled clearly and brought to the laboratory. Soil bulk density was measured by the core method (Doran and Mielke 1984). The auger samples were composited, air-dried at room temperature, and sieved to separate the whole soil (<2 mm) and soil aggregates (5 to 8 mm). Water-stable aggregate (WSA) refers to the ability of soil aggregates to resist disintegration when disruptive forces associated with tillage and water or wind erosion are applied. Soil aggregates were used to determine the aggregate size distribution and C concentration. The aggregate size fractions (represented as % by weight) of 5–8, 2.5–5, 1–2.5, 0.5–1, and 0.25–0.5 mm were obtained by the wet sieving technique (Yoder 1936). The fraction<0.25 mm was also collected. The different fractions were then separated into microaggregates (0.25–2.5 mm) and macroaggregates (>2.5 mm). Total C concentration in both aggregates and clay fraction were determined using dry combustion method (Nelson and Sommers 1986). All the chemicals used for the present study were of analytical grade (Merck, USA). The soil C pool was computed by using the following equation (Lal et al. 1998):

MgC/ha=[%C × corrected bulk density × d × 10^4 m^2/ha]/100, where Mg C/ha=megagram of carbon per hectare (1 Mg=10^6 g=1 metric ton), soil bulk density=(Mg/m^3), and d=depth in meters.

To assess the significance of C sequestration among different land use patterns (aquaculture ponds, control ponds, crop land, and forest land) and also among different particle sizes (<0.25, 0.25–2.5, and >2.5 mm) of the soils, one-way ANOVA test with post hoc multiple comparison, testing of homogeneity of variance, and descriptive statistic was performed using statistical software SPSS (version 14.0). The mean harmonic sample size was 9.0 (total N=36) for C sequestration among different land use patterns, while the mean harmonic sample size was 12.0 (total N=36) for C sequestration among different particle sizes.

Results and discussion

The C pools in the sediments of aquaculture and control ponds are presented in Table 1. The rate of sediment accumulation ranged from 8.0±1.7 to 12.0±2.8 cm with an average of 9.5±1.7 cm in the aquaculture ponds while it was 10.1±1.3 cm in the control pond. The dry bulk density of these ponds ranged from 0.7±0.2 to 0.98±0.1 Mg/m^3 with an average of 0.84±0.1 Mg/m^3 compared with 1.45±0.1 Mg/m^3 for the control pond. The WSA ranged from 54.2±35 to 74.1±22 % with an average of 62.6±10 % in these ponds compared with 53.4±15 % in the control pond. The averaged total of C was 0.84 and 0.82 % in <0.25 mm fraction, 1.9 and 1.49 % in microaggregates, and 2.8 and 2.45 % in macroaggregates for aquaculture ponds and control ponds, respectively.

The averaged total of C pool was 6.5±2 and 8.8±2 Mg/ha (Mg=10^6 g) in <0.25 mm fraction, 15.2±2 and 16.0±3 Mg/ha in microaggregates, and 22.1±3 and 26.4±3 Mg/ha in macroaggregates for aquaculture ponds and control ponds, respectively.

The estimated average annual C burial rate for aquaculture ponds monitored in this study is lower than that of control pond. The aquaculture ponds sequester C at a lower rate than the fallow pond because of lower input of external sediment and associated organic matter (OM) to aquaculture ponds than in other impoundments (Boyd et al. 2010). Moreover, aquaculture pond management minimizes OM accumulation. For example, ponds are dried at least once in a year to reduce the gaseous emissions from the bottom and also to flush out sediments by using pressurized water (Ayub et al. 1993). This intervention is needed because a thick layer of the sediment reduces the productivity of the pond. Globally, though aquaculture ponds sequester comparatively small amount of C, pond farming systems under different management practices can sequester a large amount in the long term (Adhikari et al. 2012).

The C concentration of the cropland and forest land soil is presented in Table 2. The dry bulk density of the soils under crop land and forest land was 1.22±0.03 and 1.12±0.12 Mg/m^3, respectively. The WSA in the crop land and forest land was 83.7±8 and 57.6±7 %, respectively. The total C in the soils of cropland and forest land was 1.14±0.02 and 1.57±0.16 %, respectively, in <0.2 mm fraction; 1.54±0.14 and 2.56±0.58 %, respectively, in microaggregates; and 1.62±0.16 and 2.82±0.92 %, respectively, in macroaggregates. The amount of C pool in the soils of crop land and forest land was 8.53±0.2 and 10.49±1.1 Mg/ha, respectively, in <0.25 fraction; 11.49±0.8 and 17.23±3.4 Mg/ha, respectively, in microaggregates; and 12.16±1.6 and 18.51±4.3 Mg/ha, respectively, in macroaggregates.

Considering 1.0-cm depth, the total C pool was 0.67, 0.87, 1.42, and 1.75 Mg/ha in <0.25 mm fraction; 1.55, 1.58, 1.91, and 2.87 Mg/ha in microaggregates; and 2.32, 2.61, 2.02, and 3.08 Mg/ha in macroaggregates, for aquaculture ponds, control ponds, crop land, and forest land, respectively.

The macroaggregates contained the highest total C pool, while the <0.25 mm fraction of the soil contained the lowest total C pool irrespective of the land use. The microaggregates had medium level of C pool. The total C pool was in the order of forest land>cropland>aquaculture ponds.

It has been found that there was statistically significant difference (p<0.05) between different land use patterns as determined by the robust tests of equality of means [F (3, 16)=0.000, p=0.021)]. Games–Howell post hoc test revealed that there was statistically significant difference (p<0.05) between control pond and crop land (1.46±0.67 min, p=0.000), control pond and forest land (25.68±8.1 min, p=0.000), fish pond and crop land (1.46±0.67 min, p=0.000), and fish pond and

Table 1 The C pool in aquaculture and control pond soils

Pond no.	Sediment accumulation (cm)	Dry bulk density (Mg/m^3)	Water stable aggregates (%)	Particle size (mm)	Total C (%)	C pool (Mg/ha)	C pool (Mg/ha) at 1.0-cm depth
1	8.0±1.7	0.70±0.2	67.3±23	<0.25	0.71±0.5	4.0±1	0.50
				0.25–2.5	1.25±0.8	7.4±2	0.92
				>2.5	2.35±0.4	12.9±2	1.61
2	9.0±1.3	0.98±0.1	54.8±28	<0.25	0.80±0.3	6.8±1	0.76
				0.25–2.5	1.93±0.2	16.8±2	1.87
				>2.5	3.26±0.2	28.7±4	3.18
9	12.0±2.8	0.72±0.3	74.1±22	<0.25	1.13±0.6	10.2±2	0.85
				0.25–2.5	2.70±1.1	22.9±2	1.90
				>2.5	3.02±1.2	25.6±3	2.13
10	9.0±3.0	0.94±0.2	54.2±35	<0.25	0.70±0.3	5.1±1	0.57
				0.25–2.5	1.71±0.7	13.6±2	1.51
				>2.5	2.57±0.4	21.2±1	2.35
Average	9.5±1.7	0.84±0.1	62.6±10	<0.25	0.84±0.2	6.5±2	0.68
				0.25–2.5	1.90±0.6	15.2±2	1.60
				>2.5	2.80±0.4	22.1±3	2.32
Control pond	10.1±1.3	0.98±0.2	53.4±15	<0.25	0.82±0.6	8.8±2	0.87
				0.25–2.5	1.49±1.2	16.0±3	1.58
				>2.5	2.45±1.1	26.4±3	2.61

forest land (1.46±0.67 min, p=0.000), respectively. However, there were no statistically significant differences between control pond and fish pond (p=0.887).

Levene's test for homogeneity of variance showed that the variance is not homogeneous for the C sequestration by different particle sizes (<0.25, 0.25–2.5, and >2.5 mm). Hence, robust test of equality of means was considered which showed that there were no statistical significant differences among different particle sizes [F (2, 20)=0.373, p=0.021].

The range of soil C in the upper 1 m of soil in Australia is 18–447 Mg ha, compared to a global value of 30–800 Mg ha (Carlyle et al. 2010). Carbon accumulation can be increased in the surface 0–10 cm of soil, but that is also the layer from which it can be most readily lost from Australian agricultural soils (Luo et al. 2010), and the management-induced increases of soil C in this surface layer are very vulnerable to environmental and management pressures (Sanderman et al. 2010). Generally, rarely disturbed soils of rangelands and pastures have higher C densities than regularly ploughed croplands.

Differences in SOC pool among different land uses (agricultural land, forest land, and aquaculture pond) may be attributed to the agricultural management

Table 2 The C pool in crop and forest soils

Type of soils	Soil depth (cm)	Dry bulk density (Mg/m^3)	Water stable aggregates (%)	Particle size (mm)	Total C (%)	C pool (Mg/ha)	C pool (Mg/ha) at 1.0-cm depth
Crop soils	6.0	1.22±0.03	83.7±8	<0.25	1.14±0.02	8.53±0.2	1.42
				0.25–2.5	1.54±0.14	11.49±0.8	1.91
				>2.5	1.62±0.16	12.16±1.6	2.02
Forest soils	6.0	1.12±0.12	57.6±7	<0.25	1.56±0.16	10.49±1.1	1.75
				0.25–2.5	2.56±0.58	17.23±3.4	2.87
				>2.5	2.82±0.92	18.51±4.3	3.08

practices, the variability in the silt plus clay content of the soil, and the construction of the fish pond. The SOC pool in the soil under forest was about 10.6 % as much as is emitted in the USA by combustion of fossil fuel (Sundermeir et al. 2004). Indeed, forest ecosystems can store a large amount of C pool. For example, a pine plantation can accumulate almost 250 Mg C/ha after 90 years (Birdsey 1996). Similarly, adoption of recommended management practices can increase SOC pool in soils less than 6 years of corn cultivation (Smith et al. 1999). Ismail et al. (1994) reported SOC concentration of 1,250 g C/m^2 (12.5 Mg/ha) in surface soils under conventional tillage compared with 1,740 g C/m^2 (17.4 Mg/ha) under no till practices. Buyanovsky and Wagner (1998) reported that concentration of soil organic matter (SOM) increased with increase in C inputs from residues and manure. In general, addition of biomass C enhances the SOC reserves (Smith et al. 1999). Mbah and Idike (2011) reported that afforestation and adaptation of alley cropping-based agroforestry system could store large quantities of C in soils.

Maintaining and improving the structural stability of soil is important to sequestering and stabilizing C within soil aggregates. Soil macroaggregates are vulnerable to disturbance and are structurally unstable but have the potential to physically and (to some extent) chemically bind to SOM, thereby limiting the microbial decomposition of SOC. Soil microaggregates that are essentially the building blocks of the soil macroaggregate matrix, on the other hand, retain SOC in a way that is comparatively less susceptible to physical disturbance. Therefore, the interplay of factors that includes SOC accretion, formation of macroaggregate matrices and time and land management leads to SOC sequestration.

Conclusions

From the present study, it is evident that the soils of forest land and crop land have a strong potential to sequester soil C in comparison to aquaculture ponds. Increasing SOC pool in soils could offset emissions of CO_2 from fossil fuel combustion. The techniques of SOC sequestration, such as manuring and fertilizer use, conservation tillage, mulch farming, cover crops, irrigation and restoration of degraded soils, afforestation with suitable species, and culture of suitable species on the bank of the ponds, are needed to meet the food demands of the growing population, with an ancillary benefit of SOC sequestration.

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