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Soil carbon sequestration and nutrient status of tropical rice based cropping systems: Rice-Rice, Rice-Soya, Rice-Onion and Rice-Tobacco in Sri Lanka

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ABSTRACT

Carbon sequestration increases soil fertility and reduces global warming by storing atmospheric carbon in soils. This study aimed to quantify and compare soil organic C fractions and C stocks in 4 different rice based cropping systems and investigate their variation as affected by crop rotation with upland crops. Soil nutrient availability and their relationship with chemical C fractions were also examined. Total organic C (TOC), microbial biomass C (MBC), water soluble C (WSC), $KMnO_4$ oxidizable C, pH and available macronutrients were analyzed at 0–15 and 15–30 cm depths in Rice-Rice[1] (RR), Rice-Soya (RS), Rice-Tobacco (RT) and Rice–Onion (RO) rotations on Alfisols of Sri Lanka. The data were analyzed by analysis of variance (ANOVA) on a completely randomized design (CRD) under 4 treatments with 6 replicates for each treatment. Results showed that carbon fractions and nutrient availability among different cropping systems varied significantly from one another. Under all cropping systems a higher content of all C fractions was observed in the 0–15 cm layer, except for WSC which was higher in the 15–30 cm layer because it moves to the deeper layers. The top soil layer also had a higher amount of MBC than the deeper layer, because the amount of microbial biomass and rate of microbial activity decline rapidly below the surface layer. Highest dry matter return to soil (147 g/m^2) in the RR system as paddy stubble accounted for highest amount of TOC in soil. RS system also had a higher TOC content due to the organic residues collected in soil as roots and leaf litter (67.7 g/m^2) as all dry leaves have fallen on to the soil at the time of harvesting of soyabean. However in RO system hardly any residues are added because the entire crop is removed at harvest and a significantly lower organic C content was recorded. Also the soil in RO and RT were tilled more than that used for soyabean during temporary bed preparation resulting in a relatively faster decomposition leaving significantly lower levels of C compared to RS. Change of cropping systems from RR to other annual crops such as RT and RO reduced the soil C sequestration to a significant level after 10 years of cultivation. However crop rotation change from RR to RS has maintained similar levels of C (65.18 t/ha) in RS and (63.48 t/ha) in RR. This indicated that C sequestration capacity is species specific and differences are mainly due to remaining crop residues and specific soil tillage practices used for upland crops. The study also showed that soil nutrient availability among the cropping systems varied significantly. Correlation analysis between chemical C fractions and major nutrient cations showed that there are significant correlations exist among them. The study confirmed that tropical rice based cropping systems have a great potential in storing and maintaining C in soils and thereby to facilitate nutrient availability.

1. Introduction

The potential of carbon sequestration by enhancing soil C stocks through sustainable land management has now been recognized for world agriculture (Smith et al., 2008). Crop rotations, soil tillage, fallow periods and water management are some management practices that could either reduce or increase soil C sequestration (Baker et al., 2007).

Paddy represents a large portion of global agriculture and is grown largely in South and East Asian countries as their staple food. Paddy fields are reported to have higher soil organic C storage (Pan et al., 2004) and sequestration with compared to drier croplands (Wissing et al., 2011). Organic carbon accumulation in paddy ecosystems was

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[1] RR; Rice-Rice, RS; Rice-Soya, RT; Rice-Tobacco, RO; Rice–Onion.

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faster and more pronounced than other arable ecosystems as organic matter decomposition is lessened in lowland rice fields (Wu, 2011) apparently due to excessively reduced conditions (Watanabe, 1984). Also the lack of oxygen for microbial activity under submerged conditions results in a decrease in the rate of decomposition (Jenkinson, 1988). Benbi and Brar (2009) reported that there is an incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in paddy soils as also reported by Sahrawat, 2004. In the long term, soil management controls the weathering and formation of minerals as well as accumulation of organic nitrogen in paddy soils (Kögel-Knabner et al., 2010). The mechanisms suggested for the accumulation of soil organic matter in paddy soils are identified as occlusion in aggregates, formation of organo-mineral associations, addition of pyrogenic organic matter and phyto-opal associated stabilization of organic C (Kögel-Knabner et al., 2010).

Information available on the C pools and stocks in tropical and subtropical paddy soils are restricted to some studies reported from China, India, Japan, Thailand, Indonesia and Vietnam. A study done in China reported that total SOC pool in China's paddy top soils is about 1.3 Pg, which is about 2% of the total storage in the topsoil of China (Pan et al., 2004). Wissing et al. (2011) reported an increase of topsoil organic C stocks from 2.5 to 4.4 kg m^{-2} during 50 to 2000 yrs of paddy soil management in China. Wissing et al. (2011) also reported that organic C accumulation in the bulk soil was dominated by the silt- and clay-sized fractions as also shown by Lal (2002). Nayak et al. (2012) reported that application of recommended dose of N–P–K either through organic fertilization or through inorganic fertilizer supplemented with farm yard manure or crop residues improved TOC, MBC, total SOC stocks and their sequestration rates in rice cropping systems in the Indo Gangetic Plains of India. They calculated that TOC stocks were about 6.8 g/kg in the surface 0–15 cm soil layer. Cheng et al. (2009) found higher C contents in a paddy soil chronosequence established for several hundred years in China under a rice/non-rice cropping system compared to upland soils in the same region. However their data did not include a comparison with rice alone.

Although anoxic conditions prevail during most of the time of rice growth, when the fields are drained few weeks before harvest, the redox potential increases (Jäckel et al., 2001). In addition paddy-specific water management creates a typical redox gradient in soil profiles. The highest potentials were consistently found at the surface of the roots presumably due to the influence of oxygenated water percolating into the top soil layer or due to atmospheric oxygen diffusion through shallow water (Doran et al., 2006; Schmidt et al., 2011). Oxic conditions are sustained over a longer period of time when upland crops are grown after paddy cultivation.

Management-induced change of oxic and anoxic conditions of paddy soil may affect the dynamics of organic and mineral soil constituents (Cheng et al., 2009). It is known that complexation of metals with soluble organic matter influence the solubility and mobility of metal ions in soil (Weng et al., 2002). However, Kögel-Knabner et al. (2010) reported that organic matter associated with minerals are still to be investigated for paddy soils.

Although it is known that submergence increases the quantity of soil organic matter, with long-term submergence results in the degradation of soil quality through the breakdown of stable aggregates and deterioration of soil organic matter (Mohanty and Painuli, 2004). Crop rotations are known to favour the build-up of soil organic carbon and improve soil nutrients contents in comparison with monocultures (Moore et al., 2000). Continuous monoculture will not be effective at sequestering C (Lal et al., 1998). This was further demonstrated by Campbell et al. (2007) using wheat-lentil crop rotations under upland conditions.

However crop rotations have not been studied for soil C fractions, C stocks, nutrient availability and their inter relationships in tropical paddy soils. The main objective of this study was to quantify and compare soil organic C fractions, C stocks, soil chemical and physical parameters in 4 different rice based cropping systems and to investigate their variation as affected by crop rotation with upland crops. The correlation between soil C fractions and soil nutrients were also established to understand the role of organic C fractions on nutrient availability in tropical paddy soils. We hypothesized that crop rotation changes from RR to rice with upland crops improves soil C fractions and C stocks and that C fractions affect nutrient availability in paddy soils. The information generated in this study could provide firsthand information vital to the establishment of a national carbon accounting system in the future and for maintaining sustainability of paddy soils in the tropics.

2. Materials and methods

2.1. Study area

This study was carried out on Alfisols in the North Central province of dry zone in Sri Lanka (5° 54′ N - 9° 52′ N latitude and 79° 39′ E - 81° 53′ E longitude). Four different cropping systems of paddy; Rice/Rice (RR), Rice/Soya (RS), Rice/Tobacco (RT) and Rice/Onion (RO) were selected. The sampling locations were scattered in the Divisional Secretariat Divisions of Dambulla, Awukana and Eppawala (Fig. 1). Descriptive information of the cropping systems is given in Table 1. The selected lands have maintained the same crop for >10 years. These lands were cultivated twice a year with rice in wet season while alternatively crops such as soya, onion or tobacco in dry season. The paddy fields selected were cultivated with inorganic fertilizers and no organic fertilizers were added. However the soil received a carbon input via paddy stubble during the wet season and via leaf litter and post-harvest residues of upland crops during the dry season. Inorganic fertilizer application rates are given in Table 2. Field preparation and harvesting methods are given in Table 3.

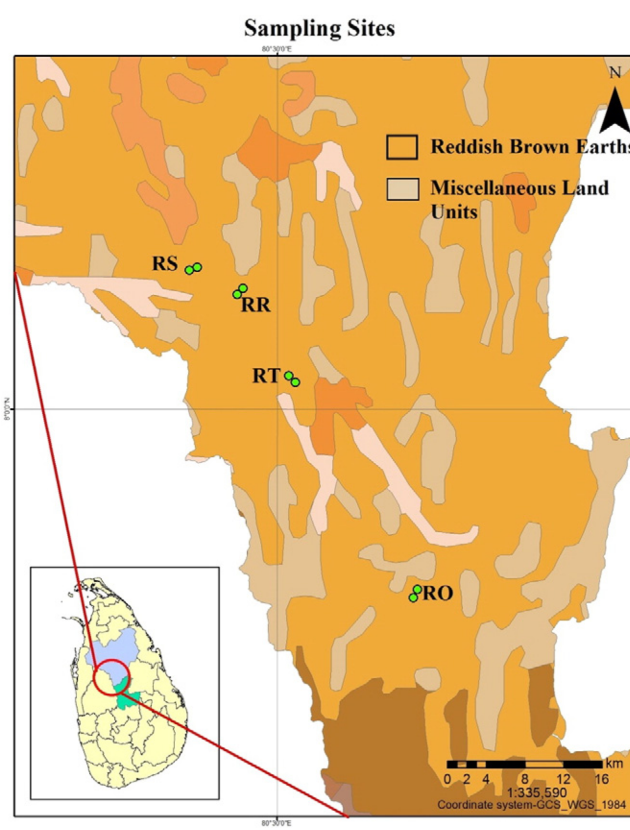

Fig. 1. Sampling locations of the study area in Sri Lanka.

Table 1
Descriptive information of different cropping systems studied.

Cropping system	Climatic region	ELE (m)	MAR (mm)	MAT (°C)	Soil texture			Textural class	Soil CO_3 content (g/kg)
					Sand (%)	Silt (%)	Clay (%)		
RR	Low country dry zone	300	1250–1500	25–27.5	69	18	12	Sandy loam	0.94
RS	Low country dry zone	300	1250–1500	25–27.5	62	28	10	Sandy loam	0.93
RO	Low country dry zone	300	1250–1500	25–27.5	64	26	10	Sandy loam	0.84
RT	Low country dry zone	300	1250–1500	25–27.5	68	21	10	Sandy loam	0.86

Rice-Rice cropping system (RR), Rice-Soya cropping system (RS), Rice-Onion cropping system (RO), Rice-Tobacco cropping system (RT), ELE, elevation; MAR, mean annual rainfall; MAT, mean annual temperature.

2.2. Soil sampling

Sampling was done during wet season just after paddy cultivation to avoid possible contamination due to the application of different inorganic fertilizers in the dry season for upland crops. For each cropping system six plots each having 20 m × 20 m area were demarcated in farmers' fields. These demarcated plots were scattered in an area of 4.04 ha (10 acre). In each plot 12 random soil samples were collected from 0 to 15 cm soil depth and pooled to form 6 composite samples. Another 12 samples were collected from 15 to 30 cm soil depth and pooled to form another 6 composite samples.

2.3. Soil sample preparation and analyses

After removing all visible organic debris, stones, plant roots the large soil aggregates were crushed and the samples were sieved using a 2 mm mesh sieve. Microbial biomass C (MBC), soil pH and available soil nutrients such as nitrate, ammonium and phosphorous were analyzed using fresh soil. The rest of the samples were air dried and ground to a powder of <0.15 mm. Additional soil samples were taken from each site, and analyzed for gravimetric water content, bulk density (Blake and Hartge, 1982) soil texture (Kettler et al., 2001) and soil CO_3 content ($CaCO_3$ equivalent) (Bundy and Bremner, 1971).

Microbial biomass carbon (MBC) was determined by using the chloroform fumigation and extraction method (Vance et al., 1987). After fumigation MBC was extracted using 0.5 M K_2SO_4 and quantified by titration method using acidified ferrous ammonium sulphate (Anderson and Ingram, 1993). The determination of TOC was carried out using acidified dichromate of organic carbon using modified Walkley's oxidation method (Baker, 1976). This method is found to be suitable for organic carbon determination in large number of samples for comparison purposes (Baker, 1976). In this study TOC was considered as equal to SOC.

Table 2
Fertilizer schedule for crops.

Land use	Season	Time of application	Fertilizer (kg/ha)		
			N	P	K
RR	Dry[a] season	Before planting	12	86	37
		Two weeks after planting	74	–	–
		Five weeks after planting	124	–	–
		Six weeks after planting	49	–	37
RS	Dry[a] season	Before planting	50	150	75
		At flowering	50	–	–
RO	Dry[a] season	Two days before planting	65	100	50
		Three weeks after planting	65	–	–
		Six weeks after planting	65	–	25
RT	Dry[a] season	Ten days after planting	24	22	34
		Twenty days after planting	24	22	34
		Thirty days after planting	24	22	34

Rice-Soya farming system (RS), Rice-Rice farming system (RR), Rice-Onion farming system (RO), Rice-Tobacco farming system (RT)
[a] During the wet season rice will be planted in all systems and same doses of fertilizer as given in RR will be added.

The labile fraction of SOC, mainly coming from the active carbon pools, was determined by the $KMnO_4$ oxidizable carbon estimation method (Weil et al., 2003). Water soluble organic carbon (WSC) was estimated by titration method using acidified ferrous ammonium sulphate (Anderson and Ingram, 1993).

2.3.1. Determination of available macronutrients

Macronutrients (K, Ca, Mg) extracted by modified Morgan extractant (NH_4OH/CH_3COOH) (McIntosh, 1969) were analyzed using atomic absorption spectrophotometer (GBC 933 AA). Soil PO_4^{3-} content was measured using molybdenum blue method (Watanabe and Olsen, 1965). Soil available N:NO_3 (Cataldo et al., 1975) and NH_4 (Lenore et al., 1989) were determined calorimetrically.

2.4. Estimation of C stocks

Carbon stocks were calculated using the following equation (Benbi et al., 2015).

$$\text{C stock (t/ha)} = \text{C content (\%)} \times \text{bulk density} \left(\text{Mg m}^{-3}\right) \times \text{depth (m)} \times 100$$

2.5. Statistical design and analysis

The data were analyzed using analysis of variance (ANOVA), on the basis of a completely randomized design (CRD) with 4 treatments and 6 replicates of each treatment. All comparisons were completed using MINITAB 16. The relationships between concentrations of different soil organic matter fractions and soil nutrients were established through correlation and regression analyses.

3. Results

The soil pH varied between 6.31 and 8.01 (Table 4). Soils of RO and RT were fairly acidic while RR and RS were fairly alkaline. Though not significant RR showed the highest pH while RO showed the lowest.

Total organic carbon (TOC) values ranged between 0.52 and 1.06% and significantly varied with different cropping systems and depth levels (0–15 cm and 15–30 cm) (Fig. 2a). Rice-Rice (RR) and RS showed the highest TOC while the lowest TOC values were observed in RO.

Microbial biomass carbon (MBC) significantly differed with land uses and soil depth and ranged between 10 and 300 mg/kg (Fig. 2b). The top layer had a higher amount (average – 110 mg/kg) than deeper layer (average – 70 mg/kg). Long term RR and RS showed significantly higher MBC content compared to RT and RO. $KMnO_4$ oxidizable C fraction varied from 596.16 mg/kg to 712.32 mg/kg (Fig. 2c) and showed a different pattern of variation than the other fractions such as TOC, MBC and WSC (Fig. 2c). Rice soya (RS) and RT showed significantly higher oxidizable C content compared to RR and RO. Water soluble carbon (WSC) ranged between 10 and 100 mg/kg (Fig. 2d) and differed significantly with cropping system. RR and RS maintained the highest WSC while RO maintained the lowest. With compared to the other organic C

Table 3
Field preparation, harvesting methods and dry matter addition during cropping.

Crop	Land preparation							
	Plowing	Tillering	Puddling	Water supply	Planting	Harvesting	Dry matte addition (g/m^2)	Organic C content (%)
Rice	+	+	+	Irrigated	Sowing	Mechanical	146.78	22
Soya	+	+	–	Irrigated	Seeding	Manual	67.7	23
Onion	+	+	–	Irrigated	Seedling	Manual	Minimal	Minimal
Tobacco	+	+	–	Irrigated	Seedling	Manual	2.86	21

fractions the interesting feature noticed here is that the C contents are higher in the bottom 15–30 cm layer than the 0–15 cm layer (Fig. 2d).

All macro nutrients studied (Ca, Mg, K) showed significant differences among the land uses and in between 2 depth levels 0–15 and 15–30 cm (Table 4). RT cropping system showed a significantly higher K and Mg content compared to the other land uses. RS showed the lowest Mg content (average 116.58 mg/kg). Ca content ranged between 282.70 and 843.36 mg/kg showing highest content in RR and lowest in RO (Table 4). Variation of $PO_{4^{3-}}$ content was almost equal except the high values in 0–15 cm layer of RO and low values in 15–30 cm layer of RR. Overall $PO_{4^{3-}}$ availability in soil was low (0–4 mg/kg) in these areas. When considering N availability, NH_4^+ and NO_3^- contents in soil were significantly higher in RR (0.66 mg/kg, 0.44 mg/kg) (Table 4).

Correlation analysis between chemical C fractions and major nutrient cations showed that significant correlations exist among some of them. MBC showed significant positive correlations with Ca (R^2 = 0.577) in the upper layer of soil (0–15 cm). Total organic C also showed positive correlation with Ca content in the 0–15 cm layer of soil (R^2 = 0.674). The correlation between Ca and WSC was significant in both soil layers (Fig. 3). Soil carbon stocks estimated in different cropping systems showed that there are differences with crop rotations. RS and RR had higher C stocks than RT and RO (Fig. 4). Although it was not significant RS maintained the highest C stocks (65.18 t/ha) followed by RR (63.48 t/ha) (Fig. 4). RO maintained the lowest amount of stable C (43.41 t/ha). It was quantified that paddy stubble add about 146.78 g dry matter to an area of 1m^2 while soya add about 67.7 g to an area of 1m^2 as root and fallen leaves (Table 3). The amount of TOC in paddy stubble was quantified as 22% and TOC in soya as 23% (Table 3). The amount of dry matter added through the root system of tobacco was estimated as 2.86 g/m^2 and TOC as 21% (Table 3).

4. Discussion

Compared to the other systems soil pH of RR increases upon long term submergence due to the consumption of protons during reduction process (Yu and Patrick, 2003). The study showed that the magnitude of increase of pH is related to the amount of organic matter as shown by the high levels of pH in RR. Because organic matter act as reducing substances that induces the reduction of oxide forms of inorganic compounds (Yu and Patrick, 2003). Comparatively low pH of RO was attributed to the acidifying effect of inorganic fertilizers and less buffer capacity of soils due to poor organic matter content with the removal of entire plant as the harvest. This could also be due to the high rates of N fertilizer added compared to other upland crops as nitrogen fertilizers have a greater acidifying effect on soils than the other fertilizers.

Rates of decomposition of organic materials which is coming through paddy stubble are considered to be slower under anaerobic conditions leading to a relatively greater accumulation of organic matter as shown in RR (Neue et al., 1997 and Lal, 2002). These partly degraded plant residues found under upland crops in many paddy soils are reported to be stabilized by occlusion in aggregates (Oades and Waters, 1991). Lal (2004) explained that the prevalent low levels of SOC concentrations in agricultural land uses are mostly due to minimal crop residue return to the soil in addition to excessive tillage and imbalance in fertilizer use. In annual crops other than rice, the major problem associated is the crop removal during harvesting creating a depletion of carbon availability for recycling in the systems. Therefore the main differences in the C content of these different cropping systems are due to the changes taking place during the dry season with upland crops as there is no difference in the wet season which is similarly under paddy.

The study clearly showed that the major factors determining the rate of carbon accumulation in these tropical soils were the quality and the quantity of litter return to soil and soil tillage (Lamb et al., 2011). As RR and RS maintained a higher TOC content probably due to the organic residues collected in soil via leaf litter and other post-harvest residues of soya (Oades and Waters, 1991). All dry leaves have fallen on to the soil at the time of harvesting of soya. However in RO no residues were added to the system because the entire crop was removed as the harvest and significantly lower organic C content was reported. In RT leaves were collected as the harvest and only the roots were remained in the field. Soil used for onion and tobacco were tilled more than those used for soya during temporary bed preparation leading to a relatively faster decomposition and leaving significantly lower level of C in these systems compared to RS.

Organic C accumulation is mainly confined to the topsoil (Kölbl et al., 2014) as shown by high amount of C in 0–15 cm layer of all 4 cropping systems. The accumulation of organic C originates from downward movement of dissolved organic C or colloidal organo-mineral associations (Li et al., 2005).

Microbial biomass is considered as a crucial parameter to evaluate the functional status of soil (Kujur and Patel, 2012). The top soil layer had higher amount of MBC than the deeper layer, because the amount of microbial biomass and rate of microbial activity decline rapidly below the surface layer (Bolton et al., 1993). It showed that plant

Table 4
Concentrations of soil available nutrients and pH in different land uses.

Ecosystem	Soil depth (cm)	K (mg/kg soil)	Ca	Mg	$PO_{4^{3-}}$	NO_3^-	NH_4^+	pH
RS	0–15	18.24^b(0.76)	623.88^b(16.75)	99.37^c(2.02)	1.20^{ab}(0.15)	0.24^{ab}(0.02)	0.21^{bc}(0.02)	7.43(0.03)
	15–30	21.64^b(0.62)	707.20^{ab}(11.67)	113.59^c(1.83)	1.07^{ab}(0.17)	0.17^b(0.01)	0.16^c(0.01)	7.75(0.03)
RR	0–15	22.65^b(0.64)	843.36^a(11.90)	119.58^c(1.16)	0.87^{ab}(0.06)	0.44^a(0.04)	0.66^a(0.05)	8.01(0.04)
	15–30	99.15^a(0.36)	827.96^a(9.15)	134.37^{bc}(3.74)	0.39^b(0.03)	0.29^{ab}(0.01)	0.55^{ab}(0.02)	7.98(0.07)
RO	0–15	41.53^b(1.68)	282.70^d(5.03)	132.87^{bc}(3.47)	2.43^a(0.03)	0.15^b(0.00)	0.34^{abc}(0.03)	6.31(0.04)
	15–30	29.92^b(1.80)	405.43^{cd}(12.22)	196.67^{ab}(5.21)	1.74^{ab}(0.43)	0.12^b(0.00)	0.38^{abc}(0.01)	6.58(0.05)
RT	0–15	91.82^a(6.27)	436.55^{cd}(24.10)	233.87^a(6.12)	1.59^{ab}(0.19)	0.15^b(0.01)	0.37^{abc}(0.02)	6.65(0.01)
	15–30	99.15^a(6.58)	567.36^{bc}(41.07)	252.87^a(16.72)	1.56^{ab}(0.20)	0.17^b(0.00)	0.34^{abc}(0.02)	6.8(0.03)

Values in the same column followed by the same letter are not significantly different at $P < 0.05$; Values for 2 soil depths were analyzed separately. Values within parentheses are standard errors. Rice-Soya cropping system (RS), Rice-Rice cropping system (RR), Rice-Onion cropping system (RO), Rice-Tobacco cropping system (RT), 0–15 cm depth (A), 15–30 cm depth (B).

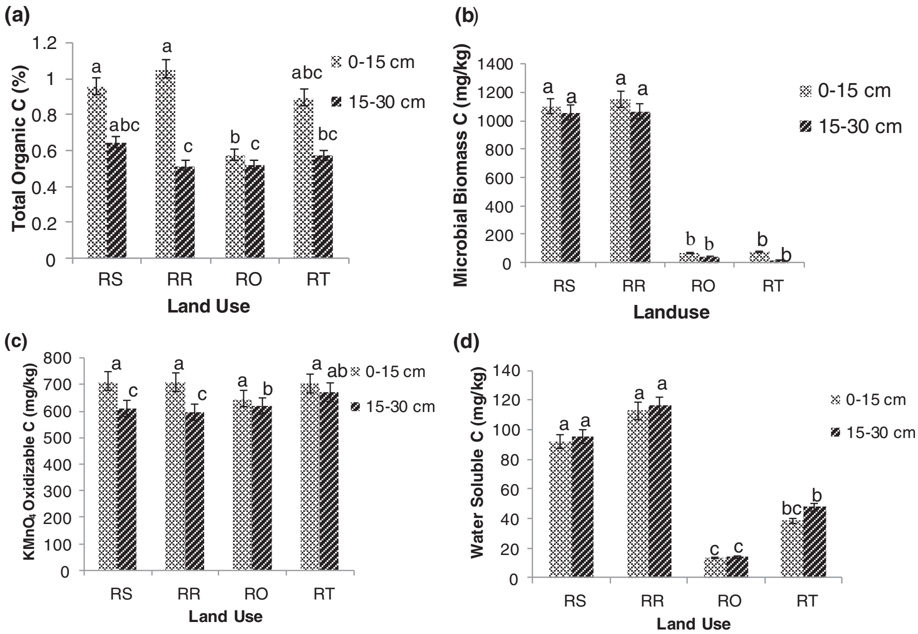

Fig. 2. Soil carbon fractions in different rice cropping systems. Rice-Soya cropping system (RS), Rice-Rice cropping system (RR), Rice-Onion cropping system (RO), Rice-Tobacco cropping system (RT). (a) Total organic C. (b) Microbial biomass carbon. (c) $KMnO_4$ oxidizable carbon. (d) Water soluble carbon (bars with the same letter are not significantly different at 5% probability level; values for 2 soil depths were analyzed separately).

cover directly affected soil microbial community significantly as shown by the high values of MBC in both RR and RS where there is a good soil cover during the dry season compared to RO and RT (Lamb et al., 2011).

It is reported that labile fraction of organic carbon is more sensitive to changes in cultivation or agricultural management practices compared to the TOC content (Haynes, 2005 and Datta et al., 2010). The plough layer depth goes up to 25 cm in these areas. This deep plowing has created destruction of soil structure. Possible leaching of labile fractions due to this destruction is reflected by low levels of labile C in 15–30 cm layer of RR and RS (Zhang and Gong, 2003). The labile C pools are primarily influenced by inputs of organic matter such as plants and animals, which contribute significantly to nutrient cycling (Hoyle et al., 2008).

Water soluble C (WSC) content accounts only for a small portion of the TOC and low compared to the MBC and $KMnO_4$ oxidizable C fractions as shown in our study (Uchida et al., 2012). Wu et al. (2006) reported that fresh crop residues are a major source of WSC. Comparatively high amount of crop residues remaining in soils of RR and RS resulted in a significantly high WSC content compared to RT and RO where there are no/very little residues remaining in soil. Water soluble C has moved down into deeper soil compartments as shown by its high content in the 15–30 cm layer (Ghani et al., 2003). Soil organic carbon (SOC) plays crucial role in soil functioning and quality by influencing soil physical, chemical and biological properties (Ding et al., 2002). Cheng et al. (2009) reported that management-induced changes of oxic and anoxic conditions results in temporal and spatial (vertical, horizontal) variations in reduction and oxidation (redox) reactions that affects dynamics of mineral soil constituents (Cheng et al., 2009).

It is reported that frequent inundation intensifies mineral weathering (Nanzyo et al., 1999) as shown by high concentration of Ca and K in RR. K is one of major nutrient that determine rice quality and yield (Oborn et al., 2005). Normally, cultivated soils have higher amounts of K with fertilization as also shown by high K content in RT. High levels of exchangeable K can interfere with Mg uptake by crops leaving significantly high concentration of Mg as observed in RT (Jayaganesh et al., 2011). Soils with low pH are reported to have low Ca availability as shown by RO in our study. However at pH values > 7.5 phosphate ions tend to react quickly with Ca and Mg to form less soluble compounds and low availability of Mg was observed in RR.

High level of nitrate stimulates organic anion synthesis resulting accumulation of cations particularly Ca^{2+} as shown by significantly high content of Ca^{2+} in RR. In many soils high levels of insoluble Ca can be released by soil acidification processes through nitrate (Technical Bulletin, Fertilizer Technology Research Center, The University of Adelaide, Australia, n.d.). Much higher Ca^{2+} concentrations are required for

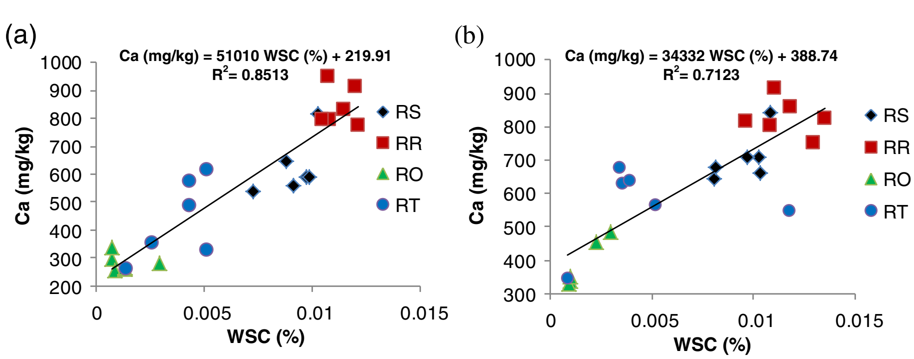

Fig. 3. Correlation between Water soluble carbon (%) and Ca^{2+} (mg/kg) (a) Ca (0–15 cm layer), (a) Ca (15–30 cm layer).

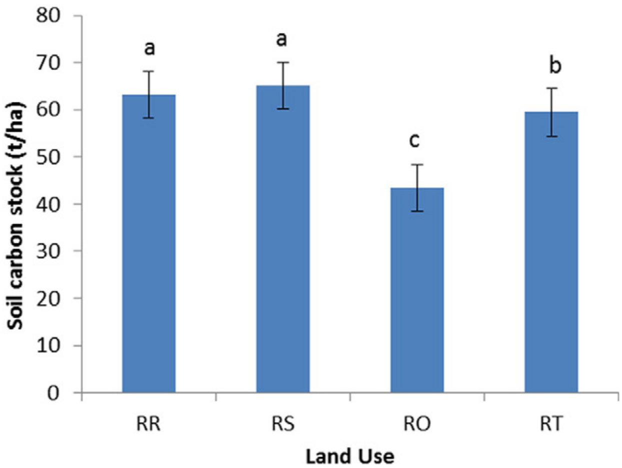

Fig. 4. Soil carbon stocks at different land uses. Rice-Soya cropping system (RS), Rice-Rice cropping system (RR), Rice-Onion cropping system (RO), Rice-Tobacco cropping system (RT).

soybean root growth (Bixby and Beaton, 1970) and therefore the availability in soil of RS is comparatively low. Higher P levels were recorded in RO land use than others. Availability of soil phosphorus is highly pH dependent. Decreases in soil pH compared to other land uses may have increase the availability of P in RO (Mitchell et al., 1952).

Li et al. (2005) and Zhang and He (2004) reported that long-term rice cropping resulted in significantly increased N contents in the plough layer as observed in RR of our study. This could be due to the direct binding of amide nitrogen in to aromatic rings and thereby reducing the possible leaching in the paddy soils (Schmidt-Rohr et al., 2004). Also the increased aeration through crop rotation improve aerobic decomposition of crop residues and act as promising management technique for improving soil N supply in lowland rice cropping systems (Pande and Becker, 2003; Cahyani et al., 2009; Gu et al., 2009).

Geochemical properties, such as the amount and degradability of organic matter or iron minerals, affect microbial activities. Conversely, microbes affect the turnover of their primary substrates (Kögel-Knabner et al., 2010). Ca^{2+} showed positive trends with increasing soluble carbon fractions such as MBC and WSC, because organic matter act as source of nutrients and also improve greater nutrient retention (Ratnayake et al., 2013) by complexation.

It is reported that the subsoil organic matter of paddy soils originates partly from leached dissolved low molecular weight organic matter released from the plough layer (Maie et al., 2004). These low molecular weight compounds are stabilized by the interacting with metal ions (Maie et al., 2004) as shown in our study by the interaction between Ca and WSC in both layers. Nguyen et al. (2004) mentioned that Ca^{2+} is responsible for a stronger binding of organic matter to soil surfaces than K^{+} as also evident from our study by the correlations existed in between Ca and all C fractions such as MBC, TOC and WSC. As we hypothesized, the study confirmed that soil organic C fractions affect soil nutrient availability in paddy soils.

Neue et al. (1997) concluded that increased SOC contents in tropical wetland soils are most probably caused by increased organic matter inputs via plant residues rather than retarded decomposition. During the wet season all cropping systems similarly received a high input of organic C through paddy stubble (Gong and Xu, 1990). Therefore the differences in soil C stocks clearly reflected the differences of remaining plant residues in the dry season under upland crops.

Crop rotation between RO and RT resulted a decrease in soil carbon sequestration, compared to that of continuous planting of flooded rice (RR). Little or no residues will remain in the soil after harvesting of onion as the entire crop is removed at harvest while only the below ground parts remained after harvesting of tobacco. It is evident that SOC stocks in the studied field sites can be maintained at optimum level through crop rotation with Soya. Although we hypothesized that crop rotation improves C sequestration, our study showed that it is not true for all crop rotations. It improved C sequestration of some crop rotations only. This knowledge would improve our understanding of different crop rotations and factors and mechanisms that affect the carbon inputs and outputs from soil, and how these might be manipulated to enhance carbon sequestration in tropical paddy soils.

5. Conclusion

After 10 years of cultivation cropping system changes of RR to other annual crops such as RT and RO reduced the soil C stocks to a significant level compared to RR on Alfisols. However crop rotation changes from RR to upland soya (RS) maintained the same level of C as in RR. Organic C accumulation is mainly confined to the topsoil layer as shown by high amount of C in 0–15 cm layer in all the 4 cropping systems studied. The main differences in the C content of these systems are clearly reflected in the differences of remaining plant residues with upland crops and soil tillage practices during the dry season as the wet season is common for all systems. The intensive tillage practices used in the bed preparation of tobacco and onion compared to soya also contributed to the stock differences of C among these 3 upland crops. The study also revealed that nutrient availability varied significantly among the cropping systems studied. RR and RS recorded higher Ca, NO_3^- and NH_4^+ availability while RT and RO recorded higher K, Mg and PO_4^{3-} availability. High level of organic matter mineralization has increased the availability of Ca in these cropping systems. Ca showed significant correlations with SOC fractions. These organic C fractions are composed of low molecular weight compounds that are stabilized by interaction with metal ions as shown by the interaction of Ca with WSC in both layers. From this study it is confirmed that rice cropping systems have a great potential in storing and maintaining C in tropical soils and thereby increase nutrient availability. Crop rotation with soya maintains high C stocks while rotation with tobacco and onion decrease C stocks.

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