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Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi arid tropics of southern India

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ABSTRACT

Reducing tillage intensity and retaining residues are important components of conservation agriculture but in small holder systems in developing countries where crop residues have alternate uses such as fodder and fuelwood, recycling or external additions of organic matter may be a possible option. Information on impacts of long term reduced tillage on soil carbon, labile organic carbon fractions and their depth distribution is scant in drylands of semi arid regions. The effect of tillage intensity (CT—conventional tillage; RT—reduced tillage and MT—minimum tillage) and sources of nitrogen (100% OS: 100% of recommended N through organic source; 50% OS +50%IOS: 50% N through organic source and 50% N through inorganic source and 100% IOS: 100% N through inorganic source) on crop yields, soil organic carbon and C fractions in an Alfisol was assessed at the end of a 10 year long term experiment. Finger millet yields decreased significantly with reduction in tillage intensity (29%). Among N sources, highest yields were recorded with substitution of 50% of the N through organic source. After 10 years, the soil organic carbon (SOC) in 0–20 cm soil layer with MT was 11% higher than with CT. The labile fractions of carbon, viz. particulate organic carbon (POC), microbial biomass carbon (MBC) and permanganate oxidizable carbon ($KMnO_4$-C) under MT were 47%, 16% and 43% higher, respectively, in comparison to CT in the 0–20 cm soil layer. The total carbon (TC) and total organic carbon (TOC) with MT were higher by 28% and 27% over CT and higher by 20% and 20% with 100%OS over 100% IOS. Labile carbon fractions revealed differential sensitivity and POC, MBC and $KMnO_4$-C are sensitive indicators to detect short term management effects. Reducing tillage intensity and applying various N sources enhanced SOC marginally and the C sequestration rate varied from 62 to 186 kg ha^{-1} yr^{-1}. Based on the study it can be recommended for substitution of 50% of the recommended N with organic source as it increases crop yields and soil carbon and could be a potential alternative for residue retention for crops which have fodder value. Reducing the tillage intensity can enhance the SOC in semi arid rainfed systems but lower crop yields under MT is a concern which needs to be addressed in order to make these systems acceptable to the farming community.

1. Introduction

Continuous and intensive tillage practices lead to loss of soil carbon and it has been estimated that globally 60–90 Pg of soil organic carbon (SOC) was lost during the last several decades (Lal, 1999). Adoption of traditional management practices including deep tillage and inversion combined with the removal of crop residues has resulted in SOC depletion which has exacerbated soil degradation and diminished the physical, chemical and biological properties of the soil (Lal, 2004). In the rainfed arid, semiarid, and sub humid regions of India, next to poor rain water management, depletion of nutrients caused by low SOC stock is an important cause of soil degradation resulting in poor soil physical quality, loss of favorable biology, and occurrence of multiple nutrient deficiencies resulting in low productivity (Srinivasarao et al., 2013). In order to meet the growing requirements of human and

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livestock population in the years to come, there will be greater pressure on the soils of rainfed regions of India to produce more which may aggravate degradation if remedial measures are not adopted. Improving SOC stock is, therefore, crucial to sustaining soil quality and enhancing agricultural productivity particularly from the rainfed regions (Srinivasarao et al., 2011c).

In India, Alfisols cover an area of 42 m ha, and are predominant in the states of Andhra Pradesh, Karnataka, Madhya Pradesh, Tamil Nadu and Uttar Pradesh (Bhattacharyya et al., 2013). Finger millet and pigeonpea are important crops grown in Alfisols of peninsular India. Finger millet was grown in about 1.5 m ha during 2009 in the state of Karnataka alone and Finger millet-pigeonpea is an important rotation widely practiced in Alfisols of peninsular India under rainfed conditions. Inherently low soil fertility status, imbalanced nutrient application, depletion of SOC, lack of crop residue recycling and micronutrient deficiency are some of the nutrition related constraints which are widespread in crops grown on Alfisols. Alfisols in peninsular India are distributed in arid and semi arid regions with low and highly variable rainfall coupled with shallow depth and low water retention characteristics leading to frequent drought stress resulting in lower crop productivity and large yield gaps. Alfisols in peninsular India support a single rainy season crop (kharif or summer) with productivity levels of 0.7–0.8 Mg ha^{-1} under semiarid conditions. Low biomass application and crop residue retention, coupled with long fallow periods which extend up to 9 months in a year result in adverse environments that do not sustain SOC levels. The magnitude of decline or enhancement of SOC due to continuous cultivation depends on the balance between the loss by oxidative processes during tillage, the quantity and quality of crop residues that are returned, and the organics added to the soils (Srinivasarao et al., 2011b).

Reducing the tillage intensity and maximizing the surface cover through retention of crop residues are the essential components of conservation agriculture (FAO, 2013). Conservation agriculture (CA), considered as an alternative strategy world over to sustain and possibly to improve the agricultural production, is widely reported to reduce soil erosion, enhance infiltration, improve soil organic stocks and enhance soil quality in varied crops and environments, while reducing risks of soil degradation under rainfed conditions (Vlek and Tamene, 2010). However, development of CA systems in rainfed agriculture is at infancy in India due to several reasons. Availability of sufficient amounts of crop residues for surface retention is a major issue in rainfed ecosystems as cropping is restricted to a single season and crop residues are used as fodder for the large livestock population. The benefits associated with reducing the tillage intensity are limited in the absence of retention of crop residues (Vanlauwe et al., 2014; Sayre et al., 2006; Derpsch et al., 2014) particularly under rainfed conditions where the soil is exposed without any vegetative cover for up to 9 months a year. Small holder farmers in developing countries generally manage intensive, mixed crop-livestock systems where animals are extremely important components and contribute to food security of the household, provide for system diversification, generate cash, spread risk, provide draft power, and transportation and are important assets for investment and savings (De Hann et al., 1997).

As crop residues for the predominant rainfed crops are valued for feed particularly by the small farmers in drier environments of northern and southern Africa, West Asia and parts of South American Andes (Wall, 2010), retaining the residues on the soil surface may not be a feasible option. Some of the alternative options suggested are gradual transition to CA by initiating only a small part of the farm (about 10% every year) and gradually expanding to the whole farm (Derpsch, 2001), introducing fodder crops into the system and integrating trees into the existing arable systems (Wall, 2010), which may not be possible under Indian situation because of the small size of the holdings (<1.0 ha), single cropping season and severe competition between the annuals and the perennials for moisture resulting in substantial reduction of crop yields under rainfed conditions (Rao et al., 1991). One of the feasible alternatives could be to use the crop residues as animal fodder and utilize the manure obtained from the farm as surface cover which can also meet part of the nitrogen requirement of the crops. Integrating farm-generated organic manure with inorganic fertilizers to increase SOC, and combining crop rotation, residue management and reducing the tillage intensity appears to be the feasible strategy under rainfed conditions (Campbell and Zentner, 1993) particularly for small farmer situations where the holdings are <1.0 ha and land degradation is severe. We hypothesized that use of manure and other sources of organic matter as a substitute for retention of crop residues together with minimum tillage will have the same benefits associated with the CA systems as practiced in other parts of the world and may favorably influence the SOC content which can sustain the productivity of the system.

Intensive cropping over the years encourages oxidative losses of C due to continuous soil disturbance, while cropping results in large scale addition of C to the soil through addition of crop residues which either results in net addition or depletion of soil C stocks (Majumder et al., 2008). Cropping systems and management practices that ensure greater amounts of crop residues returned to soil are expected to cause a net build up of the SOC stock. Identifying such systems or practices is a priority for sustaining crop productivity particularly under the rainfed conditions. As accumulation of C in soil is a slow process, and perceptible changes in SOC may not be seen over short term (Bonilla et al., 2014) and in order to understand whether C is stabilized in the soil, the SOC has to be separated into soil C fractions that are more sensitive to changes in agricultural management practices (Parton and Rasmussen, 1994). While there are several studies on the changes in SOC due to integrated nutrient management (Srinivasarao et al., 2011a,b, 2012a,b; Majumder et al., 2008), relatively few studies have focused on impacts of reduced tillage on the SOC under semi arid tropical conditions.

Agricultural practices for enhancing SOC must either increase organic matter inputs to the soil, decrease decomposition of soil organic matter (SOM) and oxidation of SOC, or a combination of both (Paustian et al., 2000). Conservation tillage systems consisting of reduced tillage, retention of crop residues are reported to accumulate soil carbon in both the temperate, tropical and Mediterranean environments (West and Post, 2002; Gonzalez Sanchez et al., 2012). Crop residues left on the soil surface adds substantial carbon to the soil and reduced tillage minimizes the soil disturbance and thus slower stubble incorporation and reduces rate of mineralization of organic matter and lowers susceptibility to physical disruptive forces (Mikha and Rice, 2004). Due to the retention of stubbles and root biomass under no till systems, SOC is physically protected from microbial decomposition through formation of stable micro and macro aggregates by forming a physical barrier between the substrates and microbes (Tripathi et al., 2014). Experiments carried out on limited scale under rainfed conditions in India have concluded that grain yields were low with minimum or reduced tillage systems during the initial years and do not have major yield advantage over conventional tillage system without incorporation of residues (Sharma et al., 2009; Venkateswarlu et al., 2010). Very few long term studies are available wherein the effects of reducing the tillage intensity was studied in association with the addition or retention of the organic matter particularly under rainfed conditions in India. Keeping this in view, the present study was made with the following objectives (i). To find out the effect of reducing the tillage intensity on crop productivity and soil carbon (ii). To study the effect of recycling of organic matter and using it as a source of nitrogen and its effect on crop productivity and iii) to evaluate the effect of long-term application of reduced tillage and crop residues on various carbon fractions and soil carbon sequestration.

2. Materials and methods

2.1. Site description

The experiment was conducted from 2001–2010 in the experimental farm of the University of Agricultural Sciences (UAS), Bengaluru (12°35′ N Latitude and 77°35′ E Longitude, 930 m above mean sea level), Karnataka in southern India. The mean annual temperature is 29.2 °C with an average rainfall of 922.7 mm and much of the rainfall is received during June to October. The soils belong to Vijayapura series and are classified as Oxic Haplustalfs. Soils are reddish brown lateritic derived from granite gneiss under sub tropical semi arid climate. They are sandy clay loam in texture, which become finer with depth. Soils are deep and have high infiltration rate and good drainage. The soil (0–20 cm soil depth) before initiation of the experiment had a pH of 5.2, electrical conductivity of $<0.20\,\mathrm{dS\,m^{-1}}$, organic carbon (Walkley and Black, 1934) content of 0.40%, bulk density of $1.30\,\mathrm{Mg\,m^{-3}}$ and 250, 9 and 160 kg available N, P and K/ha respectively.

3. Experimental design

The experiment was a laid out in split-plot design with three replications. The tillage systems were taken up in the main plots and the sources of nitrogen in the sub plots. The main plot size is 18 m × 14 m where as the sub plot size is 6 m × 14 m. The tillage systems were: conventional tillage (CT), reduced tillage (RT) and minimum tillage (MT). Description of the tillage systems are furnished in Table 1. The equipment used for tillage operations is a cultivator with 9 tynes (rigid type) and make of TAFE, Chennai. Similarly the harrow is of straight blade type and bullock drawn and make of Karshak Industries. The nitrogen requirements were met through various sources of nitrogen. 100% OS: 100% N through organic source (50% N through FYM and 50% N through Gliricidia (*Gliricidia sepium*(Jacq.) Steud.) leaves); 50% OS +50% IOS: 50% N through organic and 50% N through inorganic (25% N through FYM and 25% N through Gliricidia leaves, 50% N through urea) and 100% IOS: 100% N through inorganic source. The quantity of N applied to each crop was based on the recommendation of the Karnataka Agricultural University and fertilizer N was applied in the form of urea, phosphorus in the form of single super phosphate and potassium in the form of muriate of potash. P and K fertilsers were applied uniformly for all the treatments. The mean nutrient content of FYM was 0.8% N, 0.2% P, 0.5% K_2O and in case of gliricidia the nitrogen content was 2.6%. Quantities of FYM and the gliricidia applied were based on the nutrient recommendations for each rainy season crop. FYM and gliricidia were spread uniformly over the soil surface before sowing the crops.

Cropping in this part of India is rainfed. The cropping system is finger millet (*Eleusine coracana*L. Garten) rotated with pigeonpea (*Cajanus cajan*L. Millspaugh) or horsegram (*Macrotyloma uniflorum*Lam. Verdc). During the study period, finger millet was grown in 6 years while pigeonpea and horsegram were grown in 4 years. The crops grown and practices adopted season wise are furnished in Table 2. The experiment was planted by hand. The seeding rate adopted was $18–20\,\mathrm{kg\,ha^{-1}}$ in case of pigeonpea, $10–12\,\mathrm{kg\,ha^{-1}}$, in case of finger millet and $15\,\mathrm{kg\,ha^{-1}}$ in case of horsegram. During 2008, yields could not be realized from pigeonpea crop due to late sowing and poor crop stand and the biomass addition from the crop was not considered for calculation of total biomass recycled in to the system. Grain and biomass yields of crops were determined by manually harvesting the net plot rows every year. Above ground biomass of crops was determined 2 weeks before the harvest of crop by measuring plant samples in two $1\,\mathrm{m^2}$ quadrants outside the yield rows in each plot. Root biomass was quantified by completely excavating in case of finger millet, horsegram and by root auger in case of pigeonpea (Bolinder et al., 2002) and rhizodeposition was also quantified (Bronson et al., 1998). Litter was collected in $1\,\mathrm{m^2}$ area before harvest and expressed on hectare basis after determining the moisture content. The surface litter in both the crops was quantified to assess the biomass recycled into the system. Crop residues recycled into the soil were quantified during 2009 and 2010 only and based on these measurements, the quantities recycled into the soil were assessed for the previous years based on the stover yields.

3.1. Soil sampling and analysis

Soil samples were collected during summer 2010 from five depths, 0 to 20, 20 to 40, 40 to 60, 60 to 80 and 80 to 100 cm. A composite sample for each depth was made by mixing subsamples from two randomly selected locations within each plot. Samples were air dried, ground and sieved to 2 mm for determining carbon fractions. At the same time, a separate undisturbed soil core was taken at 20 cm interval up to one meter depth in each plot to determine the bulk density. The bulk density values thus obtained were used for calculating the depth wise carbon stocks. Soil samples for the estimation of bulk density was taken in the planted crop rows and were taken randomly using the core sampler. Mean weight diameter of water stable aggregates was determined as per Kemper and Rosenau (1986). Soil samples were also obtained from fallow land located close to the experimental plot. Samples were

Table 1
Tillage practices adopted in various tillage treatments.

Tillage	No. of tillage operations taken up	Timing of tillage operation	Instrument used	Purpose of the operation	Number of inter cultivations	Timing of tillage operation	Instrument used	Purpose of the operation
CT	3	Summer season, before sowing after the receipt of rains and just before sowing	Cultivator	Moisture conservation, seedbed preparation,	3	Thrice during vegetative growth depending on rainfall and weed growth	Blade harrow	Weeding, moisture conservation
RT	2	Before sowing after the receipt of rains and just before sowing	Cultivator	Moisture conservation, seedbed preparation,	2	Twice during vegetative growth depending on rainfall and weed growth	Blade harrow	Weeding, moisture conservation
MT	1	Before sowing	Cultivator	Opening of the furrow for sowing	1	Once during vegetative growth depending on weed growth	Blade harrow	Weeding

Table 2
Experimental details, crops cultivated and the practices adopted during the study period.

Year	Rainfall (mm) received during the cropping season (June–December)	Crop grown during the rainy season (June–December)	Variety	Month of sowing	Month of harvest	Recommended dose of NPK (kg ha^{-1})
2000	454.2	Finger millet	GPU-26	August	November	50:40:25
2001	486.6	Horsegram	Local	November	January	12.5:25:12.5
2002	220.0	Finger millet	GPU-26	July	December	50:40:25
2003	419.7	Finger millet	GPU-26	July	November	50:40:25
2004	719.8	Pigeonpea	TTB-7	June	January	25:50:25
2005	1049.0	Finger millet	MR-1	July	December	50:40:25
2006	405.6	Pigeonpea	BRG-1	July	November	25:50:25
2007	742.4	Finger millet	GPU-26	July	November	50:40:25
2009	525.1	Finger millet	GPU-26	July	November	50:40:25
2010	733.4	Pigeonpea	TTB-7	May	December	25:50:25

also collected from the control plot which was under finger millet cultivation and did not receive any inputs for the last 20 years. Though these are not part of the experiment but samples were collected for comparison.

Total carbon concentration (g kg^{-1}) in the soil was determined by the dry combustion method using carbon analyzer (Elementar) at 950 °C temperature (Nelson and Somners, 1996). For determining particulate organic carbon (POC), 10 g soil was dispersed with 30 ml of 5 g L^{-1} sodium hexa metaphosphate after shaking for 16 h and the solution was passed through a 0.053 mm sieve (Cambardella and Elliott, 1992). The solution and particles that passed through the sieve (water soluble and mineral associated C) were dried at 50 °C for 3–4 days and organic carbon was determined using Walkley and Black (1934) method. The POC concentration was determined by the difference between organic carbon in whole soil and that in the particles that passed through the sieve. Microbial biomass carbon (MBC) was estimated by fumigation incubation method for air dried soils (Jenkinson and Powlson, 1976). The oxidizable carbon fractions were estimated as defined by Chan et al., (2001). Soil organic C oxidized by 6.0 mol L^{-1} H_2SO_4 was termed as very labile pool (Fraction$_1$), the difference in SOC oxidizable by 6.0 mol L^{-1} H_2SO_4 and that of 9.0 mol L^{-1} H_2SO_4 was labile pool (Fraction$_2$), the difference in SOC oxidizable by 12.0 mol L^{-1} H_2SO_4 and that by 9.0 mol L^{-1} M H_2SO_4 was less labile pools (Fraction$_3$), and the difference between total SOC and SOC oxidizable by 12.0 mol L^{-1} H_2SO_4 was termed non labile pool (Fraction$_4$). Permanganate oxidizable carbon ($KMnO_4$-C) was determined according to the method developed by Vieira et al., (2007). Finely ground air dried soil samples were oxidized by 25 ml of 333 mmol L^{-1} $KMnO_4$. The suspensions were horizontally shaken at 60 rpm for one hour and centrifuged at 2000 rpm for 5 min. The supernatants were diluted and absorbance was measured at 565 nm with a spectrophotometer. The contents (Mg ha^{-1} or kg ha^{-1}) of SOC, POC, TC, TOC and MBC for each 20 cm depth were calculated by after factoring the bulk density of the soil layer. The total contents in the 0–100 cm depth were determined by summing the contents of all the depths.

3.2. Statistical analysis of data

The SPSS 11.5 analytical software package was used for all statistical analyses. Statistical analysis is accomplished according to the split plot design and the differences among individual treatments were determined using least significant difference (LSD) test at the 0.05 probability level.

4. Results and discussion

4.1. Effect of tillage and nitrogen sources on crop yields

Finger millet and pigeonpea grain yields were significantly influenced ($P \leq 0.05$) by tillage intensity and nitrogen sources. Higher grain yields were recorded in CT in comparison to RT and MT. Reducing the tillage intensity to a minimum (MT) reduced the crop yields and the yields recorded were significantly lower in majority of the years in comparison to the CT. On an average, finger millet yields were 29% lower with MT and 13% lower with RT over CT. In case of pigeonpea, the average yield reduction with MT was 48% and with RT it was 38% in comparison to CT. In both the finger millet and pigeonpea, RT recorded significantly higher crop yield over MT but lower in comparison to the CT but the differences between RT and CT were not significant in majority of the years

Table 3
Effect of 10 years of tillage and nutrient sources on crop yields (kg ha^{-1}) in Alfisols.

Treatment	Grain yields										Mean finger millet yields	Mean pigeonpea yields
	2000[*]	2001[#]	2002[*]	2003[*]	2004[&]	2005[*]	2006[&]	2007[*]	2009[*]	2010[&]		
CT	3128^{a}	418^{a}	2561^{a}	2677^{a}	961^{a}	3583^{a}	779^{a}	1280^{a}	2488^{a}	1025^{a}	2567	870
RT	2805^{a}	365^{a}	2297^{a}	2555^{a}	889^{a}	3531^{a}	548^{bc}	1073^{b}	1982^{b}	808^{b}	2217	719
MT	2169^{b}	315^{a}	2125^{a}	2187^{a}	556^{b}	3131^{b}	335^{c}	843^{c}	1535^{c}	642^{c}	1813	446
100% OS	1977^{h}	350^{g}	2166^{g}	2197^{i}	897^{g}	3229^{i}	577^{g}	823^{i}	1179^{i}	1198^{g}	1629	737
50% OS +50% IOS	3248^{g}	357^{g}	2396^{g}	2804^{g}	800^{hi}	3551^{g}	566^{g}	1292^{g}	2760^{g}	787^{h}	2682	683
100% IOS	2856^{g}	390^{g}	2420^{g}	2358^{h}	707^{i}	3464^{h}	519^{g}	1081^{h}	2066^{h}	491^{i}	2251	613

Different letters in a column indicate significant difference (at 5% level) between the means.

[*] Finger millet.

[#] Horsegram.

[&] Pigeonpea.

(Table 3). Horsegram yield was not significantly influenced ($P \geq 0.05$) by tillage practices.

Nitrogen sources influenced crop yields significantly ($P \leq 0.05$). The highest finger millet grain yields were observed under 50% OS +50% IOS as compared to 100% OS and 100% IOS treatments in majority of the years. 50% OS +50% IOS recorded 64.6 and 19.1% higher finger millet yields over 100% OS and 100% IOS, respectively. In case of pigeonpea, 100% OS recorded 7.9 and 20.2% higher yields over 50% OS +50% IOS and 100% IOS, respectively. Horsegram yield was not significantly influenced by nitrogen source. Combined application of organic or inorganic fertilizers was advantageous over individual application particularly in finger millet where the requirement for nitrogen is high especially during the early stages of crop growth. Availability of nitrogen is important for cereal crops, particularly during the early stages of crop growth and the treatment 50% OS +50% IOS gave comparable yields as 100% IOS. These results are in agreement with earlier studies by other researchers who reported that conjunctive application of chemical and organic manure improved grain yields in several crops rather than the individual application (Ahmad et al., 2008; Acharya et al., 1988).

Highest finger millet yields during the study period was observed during the year 2005 which coincided with the highest rainfall during the cropping period where as the lowest rainfall was received during 2002 during which finger millet could not be grown and was substituted with horsegram crop as a contingency measure. Reducing the tillage intensity influenced the growth and performance of crops due to competition from weeds during the cropping season and also by influencing the water entry into the soil profile. As rainfall is the only source of water, reducing the tillage intensity without corresponding increase in the soil cover through residues or organic matter often leads to surface sealing and loss of rainfall as runoff leading to reduced infiltration and moisture availability to the crop, particularly during the early stages of crop growth where crop coverage of the soil is limited. Alfisols have the tendency of forming crust after intense rainfall events. The minimum surface cover required for effective control of soil erosion in CA systems is about 30% (FAO, 2013). Although application of gliricidia leaves resulted in some degree of cover over the soil, rapid decomposition of the N rich leaves left the soil exposed within a short time. As soil moisture is the prime limiting factor for crop growth in semi arid tropics (SAT) regions and reducing the tillage intensity with little vegetative cover led to decreased crop growth and yields (Vanlauwe et al., 2014; Derpsch et al., 2014).

The MT had higher incidence of weeds in comparison to CT. One of the important objective of repeated tillage under rainfed conditions is to control weeds which emerge in flushes triggered by rainfall events during the crop growing period. Such weeds are controlled by repeated inter cultivation during the cropping period in CT. Although weeds were controlled to some extent in MT by one inter cultivation and one hand weeding, weed intensity was high in some of the years, impacting crop yields under MT.

4.2. Effect of tillage and nitrogen sources on carbon stocks

At 0–20 cm depth, the TC and TOC were higher by 27.6 and 19.2% in MT in comparison to CT and the differences were significant ($P \leq 0.05$). Similarly the TC and TOC are higher by 20.1 and 12.2% and 20.0 and 12.1% in 100% OS in comparison to 100% IOS and 50% OS +50% IOS ($P \leq 0.05$). The fallow land use had the highest TC and TOC which was significantly higher over all the treatments indicating that continuous cultivation over the years reduced the SOC significantly. The TC and TOC contents in RT were intermediate between CT and MT but the differences were not significant (Table 4). The 50% OS +50% IOS had intermediate TC and TOC contents between 100% OS and 100% IOS. The absolute control which did not receive any inputs had lowest levels of TC and TOC.

The total carbon stock in one meter profile (Table 4) was highest in MT followed by RT and CT. The MT had 19.2% and 19.6% higher TC and TOC over CT. The quantum of inorganic carbon stock ranged from 0.13 to 0.16 Mg/ha in various treatments. The organic carbon contributed maximum to the total carbon stocks (>95%) up to one meter depth. Organic carbon stocks were highest in MT which could be due to less soil disturbance of crop residues resulting in relatively lower oxidation of the organic matter added to the soil (root biomass, litter, etc.) resulting in slower crop residue decomposition. Among the nitrogen sources, the TOC and TC varied from 42–47 and 45–47 Mg and differences were not significant ($P \geq 0.05$). The TC and TOC content of 100% IOS was marginally higher over 50% OS +50% IOS and 100% OS. Fallow land use had highest TOC and TC content in the profile which was 51.5 and 34.2 and 51.3 and 33.9% higher over CT and 100% IOS, respectively. Continuous cultivation of finger millet with no inputs led to reduction in TOC and TC stocks. Intensive cropping over the years caused a net decrease in TOC (about 63%) compared with fallow land use. Crop cultivation consists of repeated tillage in these soils, which disturbs the distribution and stability of soil aggregates, there by exposing the organic carbon to rapid microbial decomposition which results in depletion of SOC (Quanying et al., 2014). The extent of decrease in subtropical parts of India is 30–60% (Majumder et al., 2008) and we observed a similar reduction in Alfisols under semi arid conditions.

Addition of recommended dose of nutrients with CT practices increased the TC and TOC which is evident when compared to control (which did not receive any inputs). Reducing the tillage intensity significantly improved the TOC stocks when compared to control and CT. Reducing the tillage intensity possibly reduced the rate of oxidation of carbon and helped to improve the SOC content, whereas CT practices disrupt soil aggregates exposing the previously protected organic matter to microbial action, thus accelerating its decomposition (Reicosky et al., 2002) leading to

Table 4
Effects of 10 years of tillage and nutrient sources on soil profile distribution of total carbon (TC), total inorganic carbon (TIC) and total organic carbon (TOC).

Treatmen	TC (Mg ha^{-1})		TIC (Mg ha^{-1})		TOC (Mg ha^{-1})	
	0–20 cm	0–100 cm	0–20 cm	0–100 cm	0–20 cm	0–100 cm
CT	11.23^{b}	41.89^{c}	0.02^{c}	0.13^{a}	11.21^{c}	41.75^{c}
RT	12.74^{ab}	43.18^{bc}	0.02^{bc}	0.16^{a}	12.72^{b}	43.02^{bc}
MT	14.33^{a}	49.92^{a}	0.04^{a}	0.15^{a}	14.29^{a}	49.77^{a}
100% OS	14.06^{g}	45.05^{g}	0.03^{g}	0.16^{g}	14.03^{g}	44.89^{g}
50% OS +50% IOS	12.53^{gh}	42.63^{g}	0.03^{g}	0.13^{g}	12.50^{hi}	42.49^{g}
100% IOS	11.71^{h}	47.31^{g}	0.02^{h}	0.15^{g}	11.69^{i}	47.16^{g}
Fallow	23.73	63.37	0.03	0.10	23.70	63.27
No fertilizer	9.50	38.85	0.03	0.12	9.47	38.73

Different letters in a column indicate significant difference (at 5% level) between the means.

lower TOC content (Pinheiro et al., 2004) Addition of organic matter improved the TOC stocks modestly and the improvement was observed in the 0–20 cm soil layer. Carbon stocks in 100 cm depth in 100% IOS and 50% OS +50% IOS were higher over 100% OS. Crops added significant quantities of organic matter (root biomass, stubbles, litter) which got recycled in to the soil and improved the SOC stocks in deeper layers although in modest quantity. Buildup of SOC due to cropping with the recommended levels of fertilizers was also reported from long term experiments in semi arid regions of India both in Alfisols and Vertisols and the improvement is in the range of up to 570 kg/ha/year and 410 to 1260 kg ha^{-1} year^{-1} respectively which is comparable to the values observed in the present study (Srinivasarao et al., 2012a,b).

4.3. Effect of tillage and nitrogen sources on oxidizable organic carbon and its fractions

The organic carbon was further divided into oxidizable and non labile fractions in order to assess the effect of reducing the tillage intensity and sources of nitrogen on the quantity of oxidizable carbon fractions. Reducing the tillage intensity and nitrogen sources had significant influence on oxidizable carbon fractions. At 0–20 cm depth, MT and 100% OS had higher Oxidizable C compared to other tillage and sources of nitrogen application (Table 5). The Oxidizable C constituted about 23.1–24.7% of the TOC whereas the non labile forms constituted about 73.7–76.9% of the TOC in tillage treatments. Reducing the tillage intensity resulted in accumulation of oxidizable fractions, viz., very labile and labile fractions over CT. Application of 100% OS increased the oxidizable fractions in comparison to inorganic sources of nitrogen or no addition of inputs. Continuous cropping resulted in significant decrease in oxidizable carbon in comparison to fallow land use. The relative magnitude of the pools is as follows; fraction$_1$ > fraction$_2$ > fraction$_3$ > which constituted about 18.0–22.3%, 2.3–3.9 and 1.7–2.2% of the TOC in case of tillage and 17.5–21.3%, 2.5–3.4% and 1.8–2.5% in case of nutrient application treatments, respectively. With reduction in tillage intensity, there was an increment in oxidizable carbon and also in very labile and labile carbon fractions and the increment was to the extent of 41.7, 60.4 and 50% over CT, respectively. Similarly application of large quantities of organic matter (100% OS) significantly improved the labile pools of carbon in comparison to 100% IOS.

The cumulative stocks for 0–100 cm soil depth showed higher levels of oxidizable C in MT compared to CT and RT. MT had 37.2% higher oxidizable carbon in comparison to CT and 100% OS had 38.6% higher oxidizable carbon over 100% IOS (data not presented). The oxidizable C constituted about 5.8–7.6% of TOC where as the non labile carbon constituted about 92.4–94.2% of the TOC in 0–100 cm soil depth. Fallow had the highest quantum of oxidizable C, whereas the no input control had the lowest oxidizable C. The surface soil had higher concentration of labile pools in comparison to the deeper layers. For example, in MT, the 0–20 cm soil layer had 83.5, 196.4 and 103.7% higher fraction$_1$, fraction$_2$ and fraction$_3$ contents over 20–40 cm soil depth whereas the 100% OS has 95.7, 312.8 and 94.3% higher labile pools concentration over 20–40 cm soil layer. Of the total profile oxidizable C, nearly18–24% of the oxidizable C is confined to 0–20 cm and the remaining 77–86% is in 20–100 cm profile and the extent of accumulation is relatively higher in MT (85%) and 100% OS (79%) in comparison to other treatments.

The proportion of very labile and labile fractions of carbon to the total oxidizable carbon (about 49.8–50.0% in 0–20 cm and 89.9–93.7% in 0–100 cm soil profile) in the present study is relatively higher in comparison to the rice-wheat system under humid tropical zone of India (Majumder et al., 2008) probably due to the single cropping season and low biomass turnover. The labile C pool is the fraction of SOC with the most rapid turnover rates and is sensitive to management practices and thus acts as a useful indicator for assessing the effect of different management practices as in many cases it has been observed that total SOC failed to serve as sensitive indicator (Chan et al., 2001). Quantification of labile pools provides an early indication and the mechanism by which C is lost or stabilized into soil due to management practices. The labile pool is also important from the point of view of crop production as it fuels the soil food web and greatly influences nutrient cycling for maintenance of soil quality and productivity (Majumder et al., 2007).

4.4. Effect of tillage and nitrogen sources on particulate organic carbon (POC), microbial biomass carbon (MBC) and permanganate oxidizable carbon ($KMnO_4$-C)

Some of the important labile pools of SOC widely used as indicators of soil quality are MBC, $KMnO_4$-C and POC. The POC, MBC, and $KMnO_4$-C were higher in MT in comparison to other tillage treatments and higher in 100% OS in comparison to other sources of nitrogen and at 0–20 cm depth (Table 6). The extent of improvement of POC, MBC and $KMnO_4$-C was 47.6, 16.0 and 43.2%, respectively in MT over CT in surface soil (0–20 cm). Similarly the extent of improvement of POC, MBC and $KMnO_4$-C was 37.5, 23.1 and 66.7% in 100% OS over 100% IOS in surface soil. The surface soil had higher concentration of labile pools in comparison to the deeper layers. For example, in MT, the 0–20 cm soil layer had 76.7, 83.6 and 39.0% higher POC, MBC and $KMnO_4$-C contents over 20–40 cm soil depth where as the 100% OS had 90.1, 44.9 and 88.9% higher labile pools concentration over 20–40 cm soil layer. It has been widely accepted that practices such as reduced tillage enhance labile C pools in the upper soil profile (Jacobs et al., 2010). Organic matter viz. FYM, crop residues and root C inputs are often accumulated in the surface soils; hence the higher concentration of labile pools in the surface soils (Quanying et al., 2014).

In 0–100 cm depth, the POC was highest with MT (8.4 Mg ha^{-1}) followed by RT (5.5 Mg ha^{-1}) and CT (2.5 Mg ha^{-1}) which is possibly due to slower mineralization of added organic matter

Table 5
Effect of 10 years of reduced tillage and nutrient sources on soil carbon fractions (Mg ha^{-1}) at the 0–20 cm depth.

Treatment	Total organic carbon	Oxidizable organic carbon	Very labile carbon	Labile carbon	Less labile carbon	Non labile carbon
CT	11.20^{c}	2.58	2.02^{b}	0.31^{bc}	0.25^{a}	8.62
RT	12.72^{b}	3.34	2.84^{a}	0.29^{c}	0.21^{a}	9.38
MT	14.30^{a}	3.54	2.72^{a}	0.55^{a}	0.27^{a}	10.76
100% OS	14.02^{g}	3.59	2.77^{g}	0.47^{g}	0.35^{g}	10.43
50% OS +50% IOS	12.51^{hi}	3.27	2.66^{g}	0.39^{gh}	0.22^{h}	9.24
100% IOS	11.69^{i}	2.59	2.04^{h}	0.29^{h}	0.26^{gh}	9.10
Fallow	23.70	6.19	3.64	0.34	2.21	17.51
No fertilizer	9.66	3.73	1.50	0.37	1.86	5.93

Different letters in a column indicate significant difference (at 5% level) between the means.

Table 6
Effects of 10 years of reduced tillage and nutrient sources on various pools of organic carbon at 0–20 cm depth.

Treatment	Particulate organic carbon (Mg ha^{-1})	Microbial biomass carbon (μg g^{-1})	Permanganate oxidizable carbon (mg g^{-1})
CT	1.07^{b}	105.40^{b}	0.37^{b}
RT	0.55^{c}	83.92^{c}	0.48^{a}
MT	1.58^{a}	122.31^{a}	0.53^{a}
100% OS	1.12^{g}	117.84^{g}	0.60^{g}
50% OS +50% IOS	0.83^{i}	88.12^{i}	0.41^{hi}
100% IOS	0.85^{hi}	95.71^{hi}	0.36^{i}
Fallow	2.72	73.22	0.62
No fertilizer	0.53	138.94	0.39

Different letters in a column indicate significant difference (at 5% level) between the means.

due to less frequent cultivation in MT (Data not presented). Among the nutrient sources, the treatment 100% IOS of nutrient supply had shown highest POC followed by 100% OS. Crop cultivation without addition of any inputs leads to lowest POC values (control—0.7 Mg ha^{-1}). POC has been considered as an intermediate fraction of SOC between active and slow fractions that change rapidly over time due to changes in management practices (Cambardella and Elliott, 1992) and also provides substrates for micro organisms and influences soil aggregation (Franzluebbers et al., 1999). The MBC in 0–100 cm soil profile cumulated over the individual soil layers shows that higher MBC content in RT over MT and CT and 100% OS in comparison to other sources of N (Table 6). MBC is related to the labile pools of organic matter and serves as an important reservoir of plant nutrients. The soil MBC, which represents about 1–5% of total soil organic carbon, can provide an effective indication of the improvement or deterioration of soil quality as a result of different management practices.

It is difficult to detect the changes in SOC in the short and medium term because of the large background amounts of relatively stable SOC (Gregorich et al., 1994) and the labile pools are valuable indicators of early changes in SOC stocks and hence changes in soil carbon sequestration and dynamics induced by changes in soil management practices. As the SOC build up is influenced by several factors such as climate, soil type, residue management practices, etc. often the build up or loss are not visible conspicuously and hence the need for quantification of labile fractions for understanding the mechanisms of sequestration. Higher values of labile pools in 0–20 cm depth over deeper layers could be ascribed to the greater biomass addition and turnover in surface layers in comparison to the deeper layers. The labile pools were higher in MT over CT which could be due to frequent tillage under CT may break down aggregates and exposes protected organic matter to microbial decomposition thereby increasing loss of labile C. Similarly higher labile pools in the 100% OS could be due to addition of large quantities of organic matter and plant residue might enter the labile organic C pools, provide substrate for soil micro organisms and contribute to the accumulation of labile organic C (Quanying et al., 2014). Our results indicated that reducing tillage intensity and application of nitrogen through organic source had beneficial effects on the buildup of the labile carbon pools in the surface layers and partly in 20–40 cm soil layer when compared to CT and 100% IOS of nitrogen application. In addition, POC and $KMnO_4$ are more sensitive to management practices and are also important parameters of soil health, they can be important tools in determining the sustainability of the system.

4.5. Effect of tillage and nitrogen sources on crop residues and carbon sequestration

The quantum of stubbles, leaf litter and root biomass that were recycled into the soil were quantified. The quantum of residues recycled in to soil varied from 17.63 to 51.32 Mg during the ten year experimentation through the recycling of crop residues and litter from finger millet, pigeonpea and horsegram, respectively. Among the tillage treatments, CT got highest biomass recycled in to the soil and among the N sources 50%OS +50% IOS had the highest biomass recycled due to the favourable growing conditions and the high grain and biomass production which has contributed to relatively higher root biomass and litter which got recycled in to the soil (Table 7). The quantum of organic matter added to meet the nitrogen recommendation ranged from 16.05 Mg in case of 50% OS +50% of IOS to 32.10 Mg in case of 100% OS over the entire study period. Thus considering both the organic matter added to the system and also the crop residues recycled in to the system, the highest quantity of biomass added to the system in 100% OS was 51.32 Mg whereas the 50% OS +50% IOS had 35.20 Mg/ha and the 100% of IOS has 17.63 Mg/ ha over the entire study period. The C concentrations (on an oven dry basis) in stubble ranged from 39 to 41% and roots were from 40 to 45% across the three crops. The average C concentrations in FYM and gliricidia were found to be 49% and 39%, respectively. The total carbon added to the system through various sources ranged from 8.35 to 23.16 Mg/ha and was highest in 100% OS treatment during the study period.

The SOC content during 2010, in 0–20 cm ranged from 11.02 to 12.26 Mg C ha^{-1}. The improvements in SOC from 2000 to 2010 as influenced by tillage and nitrogen sources ranged from 0.62 to 1.86 Mg C ha^{-1} (Table 8). This resulted in estimated C sequestration rates of 62 to 186 kg C ha^{-1} yr^{-1}, assuming that C sequestration was

Table 7
Return of crop residues and carbon to soil under different tillage intensity and nitrogen sources.

Treatment	Pigeonpea (t/ha/3 years)	Finger millet (t/ha/6 years)	Horse gram (t/ha/ 1 year)	Organic matter added through treatments for N (t/ha/10 years)	Total Organic matter added (Mg ha^{-1}) in 10 years	Total C added (Mg ha^{-1}) 10 years
CT	11.28^{a}	8.70^{a}	1.12^{a}	16.05^{a}	37.67^{a}	16.64^{a}
RT	9.80^{ab}	7.52^{bc}	1.02^{a}	16.05^{a}	34.85^{a}	15.47^{a}
MT	8.45^{b}	7.16^{c}	0.94^{a}	16.05^{a}	33.01^{a}	14.71^{a}
100% OS	11.30^{g}	6.48^{h}	0.99^{g}	32.10^{g}	51.32^{g}	23.16^{g}
50% OS +50% IOS	9.76^{h}	7.94^{g}	1.00^{g}	16.05^{h}	35.20^{hi}	15.61^{h}
100% IOS	10.48^{i}	7.5^{g}	1.07^{g}	–	19.14^{i}	8.35^{i}

Different letters in a column indicate significant difference (at 5% level) between the means.

Table 8
Effect of 10 years of reduced tillage and nitrogen sources on soil carbon and sequestration rate at 0–20 cm soil depth.

Treatment	Soil organic carbon content(SOC) in 2010 ($Mg\,ha^{-1}$)	Improvement in SOC from 2000 to 2010 ($Mg\,ha^{-1}$)	Carbon sequestration rate ($kg\,ha^{-1}\,yr^{-1}$)
CT	11.02^{b}	0.62^{a}	62^{c}
RT	11.18^{ab}	0.78^{a}	78^{bc}
MT	12.26^{a}	1.86^{a}	186^{a}
100% OS	12.09^{g}	1.69^{g}	169^{g}
50% OS +50% IOS	11.68^{gh}	1.28^{g}	128^{g}
100% IOS	11.64^{h}	1.24^{g}	124^{g}

Different letters in a column indicate significant difference (at 5% level) between the means.

linear from 2000 to 2010. Among tillage systems, the rate of C sequestration in MT was 186 kg C $ha^{-1}\,yr^{-1}$ as compared to 62 kg C $ha^{-1}\,yr^{-1}$ in CT. Similarly, the rate of C sequestration was 169 kg C $ha^{-1}\,yr^{-1}$ in 100% OS of nitrogen application whereas it was 124 kg C $ha^{-1}\,yr^{-1}$with 100% IOS.

The quantum of C added to the soil during the study period ranged from 14.71 to 16.64 Mg in various tillage systems and 7.50 to 23.16 Mg in various nitrogen sources. Among the tillage systems, the carbon stabilized as SOC when considered the C added to the system ranged from 3.7 to 12.6% whereas in case of nitrogen sources the carbon stabilized ranged from 7.3 to 14.8%. The extent of conversion of the applied organic matter as soil carbon stocks ranged from 3.8 to 11.6% during the study period. The extent of conversion of input C in to SOC is about 14% in humid regions of indo gangetic plains (Majumder et al., 2008), and about 14–21% in cooler, temperate climatic regions of USA (Rasmussen and Collins (1991) which are similar to the values observed in the present study but relatively higher than those obtained by Kong et al., (2005) (7.6%) under Mediterranean climatic conditions.

5. Conclusions

Ten years of finger millet/horsegram/pigeonpea cultivation, reducing the tillage intensity to the bare minimum and application of recommended quantities of fertilizers favorably influenced soil physical, biological properties and also contributed to the buildup of SOC but only modestly. N fertilization was able to increase, or at least maintain SOC even under CT systems and substitution of inorganics with organics increased the carbon buildup and labile C pools. On the other hand, no addition of inputs severely affected the crop production and caused reduction in SOC content and unfavorable changes in soil chemical and biological properties. Hence application of recommended dose of fertilizers is absolutely essential for not only realizing the optimum yields but also for SOC maintenance or build up. Utilization of crop residues as animal feed and application of farm yard manure is one of the possible alternatives for crops whose residues have fodder value under small holder situations of India.

Reducing the tillage intensity had significant negative effect on crop yields and there is a need to minimize the yield reduction for making the practice acceptable to the farming community. One of the approaches is to enhance the surface cover with either residues or organic matter for greater rainfall infiltration and moisture conservation and the other is to control weeds effectively. Controlling weeds is a challenge in reduced tillage systems as weeds emerge with every spell of rain and there are few options in terms of the post emergence herbicides. There is a need to explore pre emergence herbicides which are effective for longer duration and also newer and more effective post emergence herbicides for effective weed control.

The results of the study are particularly important in the context of developing CA strategies for rainfed systems where crop residues have fodder value and availability of biomass is scarce under rainfed environments during the dry period. The dependence of communities on the livestock systems is wide spread among the small holder systems particularly under semi arid environments in view of the significant cash returns from the livestock and convincing farmers to retain residues may be difficult. Recycling of organic matter either as farm yard manure or from leguminous trees, which can also meet part of the nitrogen requirement, can be one of the possible options with multiple advantages.

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