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Carbon Farming and Soil Organic Carbon Pools under Different Land Use and Cropping Systems in Alfisols

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ABSTRACT

The quantification of Soil Organic Carbon (SOC) pools and carbon farming potential of any land use and cropping systems are important indicators of productivity, profitability, and sustainability of that system. The objective of our present study was to evaluate the spatial and depth-wise distribution of SOC pools (active-C and passive-C) and carbon farming potential of major cropping and land use systems in Alfisols under southern agro climatic zone of Andhra Pradesh, India. We quantified active-C, passive-C pools, and SOC status in 19 different land use and cropping systems. The results indicated that SOC status and carbon farming potential were highest ($P \leq 0.001$) under forest land use (13.96 g kg^{-1} and 62.19 Mg ha^{-1}) followed by mango orchards ($\geq$ 15 years age) relatively less than 23.6%, and on par with sugarcane-vegetables 25.2%, and paddy-tomato 23.1 %. The lowest ($P \leq 0.001$) was recorded under rainfed groundnut 77.5%, followed by sugarcane-sugarcane 73.3%. The active-C pool was significantly ($P \leq 0.001$) higher in forest land use (8.79 g kg^{-1}) followed by sugarcane-vegetables (8.3 g kg^{-1}). The passive-C pool was higher ($P \leq 0.001$) under forest land use (7.98 g kg^{-1}), on par with mango orchards$\geq$ 15 years age (7.49 g kg^{-1}) and followed by paddy-tomato (5.69 g kg^{-1}) and sugarcane-paddy (5.12 g kg^{-1}). The lowest ($P \leq 0.001$) active and passive-C pools belonged to rainfed groundnut, current fallow lands, and sugarcane-sugarcane cropping systems. Of all the studied land use and cropping systems, carbon farming potential was higher under forest land use followed by mango orchards $\geq$15 years age, sugarcane-vegetables and paddy-tomato cropping systems. The potential was medium under paddy-groundnut, groundnut-tomato/vegetables, tomato-vegetables, perennial fodder plantations, casuarina and eucalyptus plantations and sugarcane-paddy cropping systems, while it was low under paddy-paddy, groundnut-groundnut, flower crops and cultivable wastes and very low under rainfed groundnut, current fallow lands, and sugarcane-sugarcane cropping systems. Thus, the present study emphasizes on the carbon farming potential, which could act as an indicator for sustainability of the different land use and cropping systems under southern agro-climatic zone.

Keywords: Andhra Pradesh, Carbon farming potential, Forest land-use, Sustainability indicator.

INTRODUCTION

The green revolution has brought much needed self-sufficiency in food grain production with special reference to wheat and rice by introduction of High Yielding Varieties (HYV's), pesticides, fertilizers and providing irrigation infrastructure facilities. Despite the success of green revolution, the productivity of majority of cropping systems in the study area under study is far from world's average productivity. However, there is evidence based plateau in the crop yields in majority of cropping systems under different land-use planning and climatic conditions. Further, there are more chances of decline

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under global climate change scenario with reduction of use efficiency of farm inputs due to the loss of SOC [percentage of organic carbon in soils estimated using method described by Walkley and Black (1934)] pool from soil. The global total SOC pool is 1,500 Pg, which is twice of the estimated quantity of earth's atmospheric carbon (720 Pg) and thrice the quantity of organic carbon present in terrestrial vegetation (Lal, 2004). The organic carbon plays a pivotal role in soil resilience under climate change scenario by improving soil aggregate stability and soil structure, water holding capacity, nutrient retention, recycling, and by enhancing the microbial diversity. It also has favorable influence on soil's cation exchange capacity, minimizing the soil erodibility and ultimately the productivity and sustainability of the production system. The organic carbon content of soil is very dynamic in nature, primarily governed by climate, especially mean annual rainfall, mean annual temperatures and land use and crop management practices. The majority of Indian soils are low (0.10-0.50%) in organic carbon content, mainly attributed to semi-arid climate with prolonged high temperatures (40-48 ^{0}C) and less crop cover, with no or less residues retention on soil surface. For sustainable productivity, it is essential to maintain a desirable level of 0.5-1.0% in agricultural soils. (Swarup *et al.,* 2000).

Soil carbon sequestration is a process in which carbon is removed from the atmosphere and stored in the soil carbon pool. This process is primarily mediated by plants through photosynthesis, with carbon stored in the form of SOC (Ontl and Schulte, 2012). The sequestration of carbon in natural soil ecosystem is of two types: First one is through soil pedogenesis in the form of calcium carbonate, and the second one is in the form of soil organic carbon through carbon inputs and has been boon for enhancing the productivity of land use/ cropping systems (Battacharyya *et al.,* 2015).The sequestration potential of the land use/cropping system has linear relation with external carbon input to that system through Farm Yard Manure (FYM), compost, and crop residues and this relation may change depending on quality of carbon input to the soil (Kong *et al.,* 2005). Further, the adopted tillage practices may hasten the decomposition of organic carbon by enhancing respiration rate of soil microbes and fauna (Reicosky *et al.,* 1997). In addition, intensive tillage exposes the physically protected organic carbon pool, i.e. encapsulated with the aggregates, to the soil microbial attack (Six *et al.,* 2000) and, finally, lack of adequate crop cover during most of the year especially in semi arid regions enables the loss of carbon pool from soil through water and wind erosion.

The amount of carbon that is sequestered in different cropping systems also depends on soil fertility, soil texture, and biomass production of the respective cropping system and land use of the study area. The legume based cropping system sequestered higher amount of SOC compared to that of soybean-wheat or paddy-paddy cropping system (Manna *et al.,* 2005). The sequestered carbon pool is protected by soil aggregation from loss due to low partial pressure of oxygen inside the aggregates and hence the carbon sequestration rate is positively correlated with degree of aggregation in different cropping systems (Manna *et al.* 2005, Hati *et al.* 2008). The carbon sequestration also depends on soil moisture content, bulk density, structural stability, porosity and nutrient distribution (IPCC, 2007). The soil management practices *viz.,* irrigation, weeding, mulching and cropping systems are well known in modifying the biological process influencing the SOC pools (Islam and Weil, 2000). The build-up of carbon in any cropping system mainly depends on residue addition to surface and sub-surface soils and its rate of decomposition (Sariyildiz and Anderson. 2003). Manna *et al.* (2012) reported that the imbalanced application of nitrogen and phosphorous fertilizers discouraged the sequestration potential of land use/cropping system in *inceptisols* and *alfisols* of central India. The highly intensive cropping system with adequate inorganic fertilizer levels of

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NPK and NPK along with FYM maintained the soil quality apart from crop sustainability and carbon sequestration potential (Manna *et al.*, 2012). The SOC sequestration is higher in 0-15 cm depth in all cropping systems compared to 15-30 cm depth, which may be due to more root biomass, addition of organic manures, and incorporation of plant residues to surface layer that eventually improved the soil physical properties (Collins *et al.* 2000).

The land use and cropping systems alter soil carbon levels, total nitrogen, phosphorous and bulk density and hence the maintenance and enhancement of SOC pool is very important to sustain the productivity of that particular land use/cropping system (Bauer *et al.* 2002). Among the land use systems, fallow land has lowest carbon content compared with grassy lands and forest land use systems. Among the social forestry tree species, casuarina and eucalyptus are preferred by farmers along the south coastal districts of Andhra Pradesh due to fast growing habit with limited care and resources and fetches quick economic returns within a short rotation of 6-7 years. The timber of these trees species is marketed to pulp and paper industries on economic front, and it maintains the organic carbon content of soil at optimum level through leaf litter fall and decay of fibrous root.

Soil carbon pools are more sensitive to changes in land-use and cropping systems than total SOC and considered as warning indicators for soil carbon dynamics (Six *et al.*, 2002). The stability or loss of soil organic carbon is understand by fractionation of SOC pools viz. active and passive carbon pool which decides the residence time of organic carbon. The labile or active carbon pool is an important indicator of nutrient recycling, maintaining soil health and productivity of the cropping system by acting as energy source for soil microbes and micro fauna (Chan *et al.*, 2001). Further, this fraction of SOM is used as a sensitive indicator of soils' health and response to changes due to management practices (Haynes, 2005).

In general, the very labile and labile pools together are considered as labile SOC pool. Whereas, passive carbon pool includes less labile and non labile pools and this carbon pool no longer acts as energy source for soil food web and is resistant to microbial decomposition (Sherrod *et al.*, 2005). The SOC pools additions and their interactions in soil and their role in enhancing the physical, chemical and biological properties of soils are conceptualized in Figure.1

The main hypothesis of the present study was that different land use and cropping

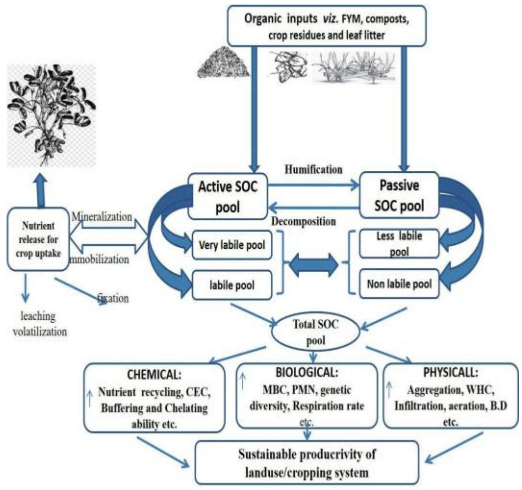

Figure.1. Conceptualized schematic framework showing the dynamics of organic carbon pools of soils under different cropping systems and land use (MBC– Microbiological Carbon, WHC- Water Holding Capacity, PMN- Potentially Mineralizable Nitrogen, BD– Bulk Density).

systems have different carbon farming potentials and SOC pools, due to the addition of an array of inputs (through leaf fall, organic manures, root biomass and exudates production, soil aeration, and soil texture), and losses through decomposition by soil microbes via tillage, soil aeration, and soil erosion determine the quality and quantity of carbon sequestration. There is little information on organic content and different SOC pools in soils of different major cropping systems and land use in southern agro-climatic zone of Andhra Pradesh, India. Hence, our main objective of this study was to quantify the carbon farming potential and status of SOC pools (*viz.*, very labile, labile, less labile and non-labile) under different land use/cropping systems in Chittoor District. This area was taken as a model where relatively many diverse cropping systems with land use planning have been practiced by the farmers of southern agro climatic zone of Andhra Pradesh, India.

MATERIALS AND METHODS

The present study was carried out during the years 2018 and 2019 in Chittoor District of Andhra Pradesh, India, which falls under southern agro-climatic zone (located between 12-37 to 14-8 of Northern latitude and 78-33 to 79-55 of Eastern longitude) with mean elevation of 53–183 m from Mean Sea Level (MSL). The total geographical area of the district is 1,515,000 ha out of which only 346,000 ha area under cultivation. The onset of South West monsoon is first week of June, which continues till third week of September, whereas North East monsoon enters first week of October continues up to last week of December with an average annual rainfall of 934 mm. The S.W monsoon (June-Sep) receives 438 mm (47%), NE monsoon (Oct-Dec) receives 396 mm (42.3%) rainfall, winter period (Jan- Feb) receives only 12 mm and 88 mm of rainfall falls during summer period (March-May). The mandals (local administrative unit) comes under western region of the zone received through SW monsoon. Whereas, mandals in eastern region received through NE monsoon and the amount of rainfall is gradually low from eastern mandals to western mandals of the study area. In summer, the temperature varies between 24.4 to 38.0^{0}C and sometimes reaches to 42.0^{0}C whereas; in winter the temperature varies 17.4 to 31.6^{0}C. The study area witnessed different major land use and cropping systems *viz.*, (1) Rice based, (2) Sugarcane based, (3) Vegetable based, (4) Rainfed groundnut, (5) Casuarina and eucalyptus plantations, (6) Mango orchards, (7) Fodder crops based, (8) Flower crops based, (9) Forest land use, (10) Fallow land use, and (11) Waste land use systems. The detailed site characteristics and management practices adopted in each land use and cropping system were collected from the farmers during preliminary survey and are presented in Table 1.

Soil Sample Collection and Processing

To collect soil samples, three locations were fixed in different directions representing each identified land use/cropping system in the study area. Surface (0-15 cm) and sub surface (15-30 cm) soil samples were collected from four random places, mixed thoroughly and composite sample was made from the area of 1.0 ha. The latitude and longitude were recorded from every sampling site with the help of GPS and the location map was prepared using Arc GIS version 9.3.2 (Figure 2). At every location, the bulk density was measured with soil core sampling method, which is most accepted method for agricultural soils (Casanova *et al.*, 2016). The metallic core with 60 mm diameter and 100 cc internal volume was hammered into the soil at 0-15 cm depth (Walter *et al.*, 2016) and sample retained within the core was transferred to pre weighed aluminum box and kept in oven at 104^{0}C for 48 hours. The soil bulk density (Mg m^{-3}) was measured as percentage mass of dry soil

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Table 1. Site characteristics under different land use/cropping systems of the study area.

S No	Land use/Cropping systems	Age	Species/Crop variety	Management practices
1	Rice based cropping system	6-8 years	BPT 5204 and ADT 37	Puddling, transplantation and organic manure @ 10 t ha^{-1} along fertilizer application 80-60-40 (N-P-K) kg ha^{-1}
2	Sugarcane based cropping system	6-8 years	99R1299 and 2000a213	FYM application @ 10 t ha^{-1} and N-P-K @ 225-100-116 kg ha^{-1}
3	Vegetable based cropping system	6-8 years	Tomato hybrids (private), beans and chillies	FYM @ 25 t ha^{-1} and N-P-K @ 120-60-80 kg ha^{-1} under drip and furrow irrigations
4	Rainfed groundnut	10 years	Kadiri-6	No organic manure application and N-P-K @ 20-40-0 kg ha^{-1}
5	Casuarina and eucalyptus plantations	6-8 years	Local species	No soil disturbance and drip irrigation during initial years
6	Mango orchards	$\geq$ 15 years $\leq$ 5 years	Totapuri, Beneshan	Intercropping with horsegram, groundnut under rainfed situation in $\leq$ 5 years orchards but no soil disturbance under older orchards$\geq$ 15 years
7	Fodder crops based	6-8 years	CO-2, Napier grass	Raising on ridge and furrow method and Urea application
8	Flower crops based	6-8 years	Rose, Chrysanthemum	Organic manures @ 5 t ha^{-1}
9	Forest land use	➢ 50 years	*Red sanders*, *Shorea talura*, *Shoreath umburggaia*, *Terminalia pallid* and *sandal wood*	Natural un disturbed ecosystem
10	Fallow land use	2-3 years	Weeds (1-2 years age)	No management
11	Wasteland use	5 years	Small shrubs (4-5 years age)	No management

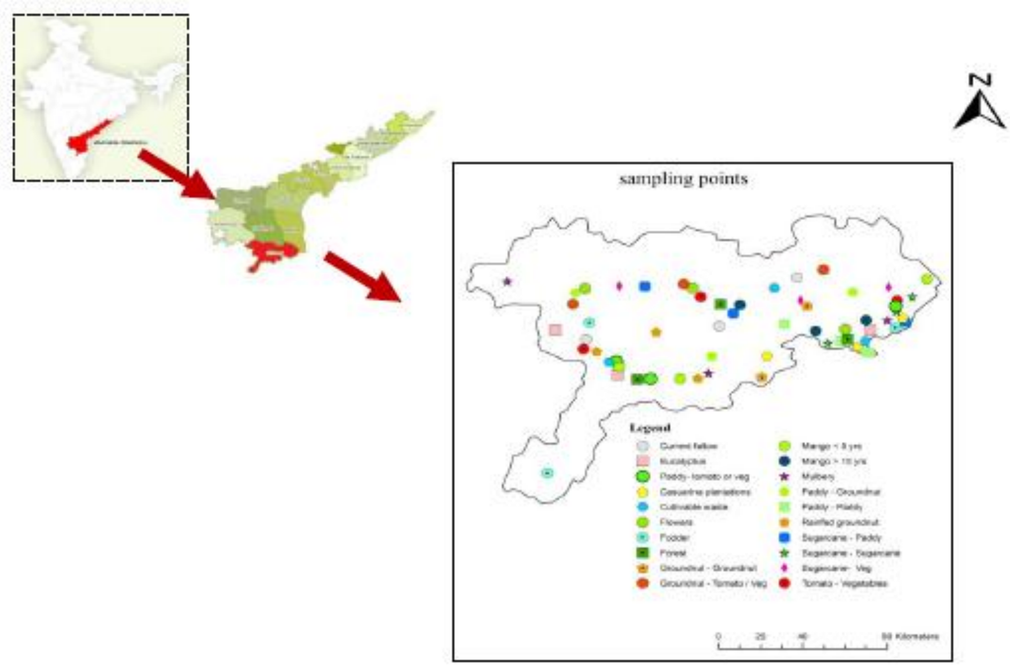

Figure 2. Location map of study area with depiction of different land use and cropping systems of the study area using Arc GIS version 9.3.2.

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to the volume of metallic core (Yang *et al.*, 2016). The soil samples were brought to the laboratory and the plant debris, roots, and stones were separated and the samples were air dried, pounded and passed through the 2 mm sieve. This fine earth was again pounded and passed through 0.2 mm sieve for estimation of soil organic carbon stock.

Laboratory Analysis

The Walkley–Black method is a standard method for estimating organic carbon, but due to incomplete digestion of organic carbon with low recovery percentage of only 77% (Walkley and Black, 1934) correction factor of 1.33 is used to adjust the organic carbon recovery. The modified Walkley-Black method ensures full oxidation of organic carbon content with external heat is provided at 150^0C for about 30 minutes in addition to the heat of dilution (Mebius, 1960). Hence, no correction factor was needed. The organic carbon stock in different land use/ cropping system at different depth was calculated by multiplying the bulk density (Mg m^{-3}) by soil organic carbon content (Poeplau *et al.* 2017)

SOC stock (Mg ha^{-1})= Organic carbon %×Bulk density (Mg m^{-3})×Soil depth (cm).

Soil organic carbon has been categorised into different pools depending upon the lability in the soil-pant system. The easily mineralizable fractions are considered most labile and have very low residence time. The other fractions have relatively longer existence period in soil and are termed as slow or resistance fractions or non-labile fractions. These fractions vary in soils based on soil texture, management, and climatic conditions. This labile and non-labile fraction of organic carbon was quantified with sequential oxidation or hydrolysis (Kolar *et al.,* 2011).

For fractionation of different oxidizable organic pools under different land use/ cropping system, we used Walkley-Black methodology with varied concentration of sulfuric acid (H_2SO_4) *i.e* 12, 18 and 24N concentrated solutions with same concentration of potassium dichromate ($K_2Cr_2O_7$) (Chan *et al.,* 2001). The 0.2 mm sieved sample (1 g) taken in the three different sets and added 10 mL of 1N $K_2Cr_2O_7$ to each set. The concentrated sulfuric acid was added to three sets at the rate of 5, 10, and 20 mL separately and swirled the flask to ensure complete mixing of the sample with the reagents for quick digestion. The concentration of different pools of organic carbon viz. very labile, labile, less labile, and non-labile based on oxidizability by heat of dilution.

Active–C pool:

Very labile–C (ppm) = Amount of SOC calculated in first set *i.e.* 5 mL H_2SO_4 and 10 mL

$K_2Cr_2O_7$ (0.5:1)

Labile–C (ppm)= Amount of SOC calculated in second set *i.e.* 10 mL H_2SO_4 and 10 mL

$K_2Cr_2O_7$ (1:1)–SOC in first set (0.5:1)

Passive–C pool:

Less labile–C (ppm) = Amount of SOC calculated in third set *i.e.* 20 mL H_2SO_4 and 10 mL

$K_2Cr_2O_7$ (2:1)–SOC in second set (1:1)

Non-labile–C (ppm)= Total carbon by modified Walkley-Black method (%)×10000–SOC measured in third set (2:1)

Statistical Analysis

Data subjected to one-way Analysis Of Variance (ANOVA) using SPSS ver. 2.0 package (IBM, India). Different sampling sites for each land use and cropping systems were considered as replicates. Further, the mean separation of SOC under different land uses and cropping systems of the study area was evaluated at 95% confidence interval using Tukey's Honestly Significant Difference (HSD) post hoc test.

RESULTS

Distribution of Active and Passive-C Pools

At Surface Horizon (0-15 cm depth)

The SOC pools vary with the adopted land use and cropping systems, management, and soil depth. At surface horizon (0-15 cm), a higher

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active-C pool was recorded compared to passive-C pool in the majority of cropping systems and land use, except mango orchards ≥15 years and ≤ 5 years and sugarcane-paddy cropping systems in which higher passive-C over active-C was recorded. The higher active-C was recorded in forest land use (8.79 g kg^{-1}) followed by paddy-tomato (5.84 g kg^{-1}) and groundnut-groundnut (4.77 g kg^{-1}) and lowest (P≤ 0.001) was recorded under rainfed groundnut (1.97 g kg^{-1}) and current fallow land (2.32 g kg^{-1}), whereas, passive-C reported highest P≤ 0.001) under forest land use (7.98 g kg^{-1}) followed by mango orchards ≥ 15 years (7.49 g kg^{-1}) and sugarcane-paddy cropping systems (5.12 g kg^{-1}). The lowest (P< 0.001) passive-C was recorded under rainfed groundnut (1.45 g kg^{-1}) (Table.2 and Figure 3).

The less labile fraction of active-C pool was higher in mango orchards ≥ 15 years (4.66 g kg^{-1}) followed by forest land use (4.21 g kg^{-1}), followed by sugarcane-vegetable (3.02 g kg^{-1}); and the lowest (P≤ 0.001) was reported under paddy-groundnut (0.53 g kg^{-1}), sugarcane-sugarcane (0.68 g kg^{-1}), and rainfed groundnut (0.79 g kg^{-1}) cropping systems. But in the non-labile fraction of passive-C pool, the highest (P≤ 0.001) was recorded under forest land use (3.78 g kg^{-1}) followed by mango orchards ≥ 15 years (2.82 g kg^{-1}), and paddy-groundnut (2.39 g kg^{-1}) cropping systems; and the lowest (P≤ 0.001) was recorded under rainfed groundnut (0.66 g kg^{-1}) and current fallows (0.97 g kg^{-1}) cropping systems (Table.2).

At Sub-Surface Horizon (15-30 cm depth)

The highest (P≤ 0.001) active-C was recorded under forest land use (7.01 g kg^{-1}) followed by paddy-tomato (5.52 g kg^{-1}) and sugarcane-paddy (5.52 g kg^{-1}) cropping systems; and the lowest (P≤ 0.001) was recorded under rainfed groundnut (1.21 g kg^{-1}), sugarcane-sugarcane (1.37 g kg^{-1}) and current fallow (1.52 g kg^{-1}). Whereas, the passive-C pool also varied significantly (P≤ 0.005) with cropping systems and was found the highest under mango orchards ≥ 15 years (6.49 g kg^{-1}) and the lowest (P≤ 0.005) was recorded under current fallows (1.33 g kg^{-1}), rainfed groundnut (1.65 g kg^{-1}), and sugarcane-sugarcane (1.66 g kg^{-1}).

Among the fractions of passive-C pool, less labile-C recorded highest (P≤ 0.005) under mango orchards ≥ 15 years (4.36 g kg^{-1}) followed by paddy-groundnut (2.40 g kg^{-1}), and sugarcane-vegetable (2.16 g kg^{-1}) cropping systems; and the lowest (P≤ 0.005) was observed under sugarcane-paddy (0.23 g kg^{-1}) followed by perennial fodders (0.44 g kg^{-1}) and current fallows (0.67 g kg^{-1}). The non-labile-C fraction of passive-C pool was highest (p≤0.001) under forest land use (2.49 g kg^{-1}) followed by paddy-tomato (2.30 g kg^{-1}) and mango orchards ≥ 15 years (2.13 g kg^{-1}); and the lowest (P≤ 0.001) was noticed in rainfed groundnut, current fallows (0.66 g kg^{-1}), and sugarcane-sugarcane (0.79) land use systems (Table 3).

Total SOC Content and Stocks

Total SOC content and stocks present in the surface and sub surface soil layers were significantly (P≤ 0.001) influenced by the land use and cropping system. The surface layers (0-15 cm) had higher SOC content and stocks than sub surface layers (15-30 cm), except eucalyptus plantations, which showed a reverse trend in distribution of carbon stocks and SOC stocks were equally distributed in both soil depths under mango orchard ≤ 5 years, paddy-groundnut, and rainfed groundnut cropping systems. At surface horizons, highest carbon content and stocks were reported in forest land use (16.78 g kg^{-1} and 31.9 Mg ha^{-1}) followed by mango orchards ≥ 15 years (12.25 g kg^{-1} and 23.33 Mg ha^{-1}), sugarcane-vegetable (12.38 g kg^{-1} and 23.38 Mg ha^{-1}) and paddy-tomato (11.53 g kg^{-1} and 19.84 Mg ha^{-1}). Whereas, lowest SOC content and stocks (P≤ 0.001) was recorded under rainfed groundnut (3.42 g kg^{-1} and 6.06 Mg ha^{-1}) was followed by current fallows (4.18 g kg^{-1} and 8.41 Mg ha^{-1}) and sugarcane-sugarcane (4.42 g kg^{-1} and 10.15 Mg ha^{-1}) at surface depth (0-15 cm). In sub surface horizons(15-30cm), forest land use (11.14 g kg^{-1} and

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Table 2. SOC pools and carbon farming potential at 0-15 cm depth under different land use and cropping systems.

S No	Land use/ Cropping system	Active-C pool (Very labile+ Labile - C) (g kg^{-1})	Passive-C pool (g kg^{-1})	less labile - C (g kg^{-1})	Non-labile pool–C (g kg^{-1})	Total SOC (g kg^{-1})	Carbon farming potential (Mg ha^{-1})
1	Mango orchards ≥15 years age	4.77^{bcde}	7.49^{a}	4.66^{a}	2.82^{b}	12.25^{b}	23.33^{a}
2	Mango orchards ≤5 years age	3.64^{cdef}	3.99^{cd}	2.22^{bc}	1.77^{defg}	7.63^{de}	15.78^{cd}
3	Sugarcane-paddy	3.01^{ef}	5.12^{bc}	3.01^{b}	2.11^{bcdef}	8.13^{de}	15.35^{cd}
4	Sugarcane-vegetables	8.30^{a}	4.08^{cd}	1.63^{cd}	2.45^{bcd}	12.38^{b}	23.38^{b}
5	Sugarcane-sugarcane	2.51^{f}	1.91^{ef}	0.68^{ef}	1.23^{ghi}	4.42^{fg}	10.15^{de}
6	Paddy-tomato	5.84^{b}	5.69^{b}	3.02^{b}	2.66^{bc}	11.53^{bc}	19.84^{bc}
7	Paddy -groundnut	5.22b^{cd}	2.92^{de}	0.53^{f}	2.39^{fgh}	8.14^{de}	15.84^{de}
8	Paddy-paddy	3.78^{bcdef}	2.54^{ef}	0.61f	1.93^{cdefg}	6.31^{defg}	12.72^{de}
9	Rainfed groundnut	1.97^{bcde}	1.45^{f}	0.79^{def}	0.66^{i}	3.42^{defg}	06.06^{de}
10	Groundnut-groundnut	4.77^{bcde}	2.35^{ef}	0.70^{ef}	1.65^{efgh}	7.12^{def}	13.24^{cde}
11	Groundnut-tomato/vegetable	5.46^{bc}	3.16^{de}	1.53^{cde}	1.63^{fgh}	8.62^{cd}	15.38^{cd}
12	Tomato-vegetables	5.39^{bc}	3.24^{de}	0.75^{def}	2.49^{bcd}	8.63^{cd}	15.76^{cd}
13	Flower crops	4.18^{bcde}	2.66^{def}	1.08^{def}	1.58^{fgh}	6.83^{defg}	13.68^{cde}
14	Perennial fodder crops	4.43^{bcde}	2.26^{ef}	0.28^{f}	1.98^{cdef}	6.69^{defg}	13.09^{de}
15	Casuarina plantations	4.93^{bcde}	2.45^{ef}	0.83^{def}	1.62^{fgh}	7.39^{de}	14.27^{cde}
16	Eucalyptus plantations	3.62^{cdef}	2.46^{ef}	0.85^{def}	1.61^{fgh}	6.08^{defg}	11.37^{de}
17	Current fallow lands	2.32^{f}	1.86^{ef}	0.89^{def}	0.97^{hi}	4.18^{g}	8.41^{e}
18	Cultivable waste lands	3.25^{def}	2.44^{ef}	1.03^{def}	1.41^{fgh}	5.68^{efg}	10.53^{de}
19	Forest land use	8.79^{a}	7.98^{a}	4.21^{a}	3.78a	16.78^{a}	31.90^{a}
	F value	5.953**	13.771**	16.343**	7.761**	10.335**	6.547**
	p value	0.000	0.000	0.000	0.000	0.000	0.000

$^{a-i}$ Same set of alphabets indicates insignificant difference (Tukey's HSD). ** Significant at 1% level.

Table 3. SOC pools and carbon farming at 15-30 cm depth farming under different land use and cropping systems.

S No	Land use/Cropping system	Active-C pool (Very labile+Labile - C) ($g\ kg^{-1}$)	Passive-C pool ($g\ kg^{-1}$)	less labile - C ($g\ kg^{-1}$)	Non labile pool–C ($g\ kg^{-1}$)	Total SOC ($g\ kg^{-1}$)	Carbon farming potential ($Mg\ ha^{-1}$)
1	Mango orchards ≥15 years age	2.73^{cdef}	6.49^{a}	4.36^{a}	2.13^{abc}	9.22^{abc}	17.04^{abc}
2	Mango orchards 5 years age	3.74^{bcd}	3.72^{bcdf}	1.99^{bc}	1.72^{abcdef}	7.46^{bcde}	15.63^{abcde}
3	Sugarcane-paddy	5.22^{ab}	1.83^{ef}	0.23^{d}	1.60^{bcdefg}	7.05^{bcdef}	13.13^{bcdefg}
4	Sugarcane-vegetables	4.07^{bcd}	4.43^{ab}	2.16^{bc}	2.27^{ab}	8.50^{abc}	16.42^{abcd}
5	Sugarcane-sugarcane	1.37^{f}	1.66^{ef}	0.87^{cd}	0.79^{ghi}	3.03^{gh}	5.52^{h}
6	Paddy-tomato	5.52^{ab}	4.43^{ab}	2.13^{bc}	2.30^{ab}	9.95^{ab}	18.16^{ab}
7	Paddy-groundnut	3.63^{bcde}	4.21^{bc}	2.40^{b}	1.82^{abcde}	7.85^{abcde}	15.19^{abcdef}
8	Paddy-paddy	2.49^{cdef}	2.63^{bcdef}	1.45^{bcd}	1.18^{defghi}	5.12^{defgh}	10.06^{defgh}
9	Rainfed groundnut	1.21^{f}	1.65^{ef}	1.06^{bcd}	0.59^{i}	2.85^{h}	6.14^{h}
10	Groundnut-groundnut	2.22^{cdef}	2.32^{cdef}	0.93^{bcd}	$1.39^{cdefghi}$	4.54^{efgh}	8.49^{gh}
11	Groundnut-tomato/Vegetable	2.90^{cdef}	3.05^{bcdef}	1.61^{bcd}	1.43^{cdefgh}	5.94^{cdefgh}	11.30^{cdefgh}
12	Tomato-vegetables	3.36^{bcdef}	2.71^{bcdef}	1.37^{bcd}	$1.34^{cdefghi}$	6.07^{cdefgh}	10.77^{cdefgh}
13	Flower crops	2.20^{cdef}	2.45^{bcdef}	1.38^{bcd}	1.07^{efghi}	4.65^{efgh}	8.86^{fgh}
14	Perennial fodder crops	4.53^{bc}	1.79^{ef}	0.44^{d}	$1.35^{cdefghi}$	6.33^{cdefg}	10.98^{cdefgh}
15	Casuarina plantations	2.85^{cdef}	2.16^{cdef}	0.85cd	$1.31^{cdefghi}$	5.02^{defgh}	8.71^{fgh}
16	Eucalyptus plantations	4.66^{bc}	3.45^{bcde}	1.44^{bcd}	2.01^{abcd}	8.11^{abcd}	15.80^{abcde}
17	Current fallow lands	1.52^{ef}	1.33^{f}	0.67^{cd}	0.66^{hi}	2.85^{h}	5.44^{h}
18	Cultivable waste lands	1.89^{cdef}	2.12^{def}	1.19^{bcd}	0.93^{fghi}	4.01^{fgh}	9.85^{efgh}
19	Forest land use	7.01^{a}	4.12^{bcd}	1.63^{bcd}	2.49^{a}	11.14^{a}	21.56^{a}
	F value	4.108**	3.295**	2.959**	3.814**	4.298**	4.035**
	P value	0.0001	0.0011	0.0027	0.0003	0.0001	0.0001

[a-i] Same set of alphabets indicates insignificant difference (Tukey's HSD).** Significant at 1% level.

21.56 Mg ha^{-1}) recorded higher ($P \leq 0.001$) carbon stocks followed by paddy-tomato (9.95 g kg^{-1} and 18.16 Mg ha^{-1}), mango orchards $\geq$ 15 years (9.22 g kg^{-1}and 21.56 Mg ha^{-1}), sugarcane-vegetable (8.50 g kg^{-1} and 16.42 Mg ha^{-1}) cropping systems; and the lowest ($P < 0.001$) was recorded under rainfed groundnut (2.85 g kg^{-1} and 6.14 Mg ha^{-1}) followed by current fallows (2.85 g kg^{-1} and 5.44 Mg ha^{-1}), and sugarcane- sugarcane (3.03 g kg^{-1} and 5.52 Mg ha^{-1}), (Figure4).

DISCUSSION

The SOC pools and carbon farming potential of soils in southern agro climatic zone are significantly influenced by the type of cropping system and land use. The variations are mainly attributed to differences in organic carbon additions via leaf litter addition, organic manures addition, crop residue recycling, root biomass and exudates production, and management practices of that particular system (Lal 2008); and the SOC stocks of different land use and cropping systems of the study area is a function of carbon balance between additions through FYM, crop residues, root biomass, and losses due to microbial decomposition and soil erosion (Sariyildiz and Anderson, 2003).

Soil Organic Carbon Pools

The active-C pool was higher than passive-C pool in surface horizons (0-15 cm depth) in all the cropping systems and land uses under study. This may be due to the addition of easily decomposable organic manures, crop residues, and root biomass production that are relatively higher in surface horizon than sub surface horizon (Bruun *et al.* 2013).

The active-C pool was higher under forest land use system due to continuous addition of easily decomposable litter through leaf fall and sufficient tree cover protection of the active-C from further decomposition and on par with sugarcane-vegetable, paddy-tomato, groundnut-tomato and tomato-vegetables cropping systems due to regular application of farm yard manure to the vegetables. In contrast, rainfed groundnut and current fallow lands recorded lowest active-C, which is mainly attributed to the coarse textured soils, limited and non-application of organic manures and plant nutrients. The passive-C pools (less labile and non-labile-C pools) were higher under forest land and mango orchards $\geq$ 15 years, mainly due to the addition of leaf litter, which is rich in lignin and hemicellulose, followed by incorporation that favors micro aggregates, which ultimately protect the carbon from physical breakdown by restricting access to microbes and oxygen. The lowest active and passive-C pools under rainfed groundnut and current fallow lands were due to limited application of organic manures coupled with poor crop cover during most of the year, resulting in the loss of SOC pools through microbial breakdown. On contrary, the low SOC pools in soils of sugarcane-sugarcane system might be due to repetitive trash burning that resulted in loss of different organic pools and specifically active-C pool (Lungmuana *et al.*, 2018). In sugarcane based cropping systems, sugarcane-vegetable, which is more sensitive to management practices, had higher active-C pool over others due to regular application of organic manures (Haynes, 2005). This active-C pool is sharply reduced with sugarcane-paddy cropping system, while increase in passive-C was observed mainly because puddle condition might increase this pool by slowing down the decomposition process, which leads to the accumulation of less labile and non-labile fractions under prolonged submergence (Benbi *et al.*, 2012). The paddy-paddy cropping system lowers the active- and passive-C compared with paddy-tomato and paddy-groundnut mainly due to intensive puddling, which disintegrate the macro and micro aggregates and, subsequent, loss by microbial oxidation (Six *et al.*, 2000). In all the paddy based cropping

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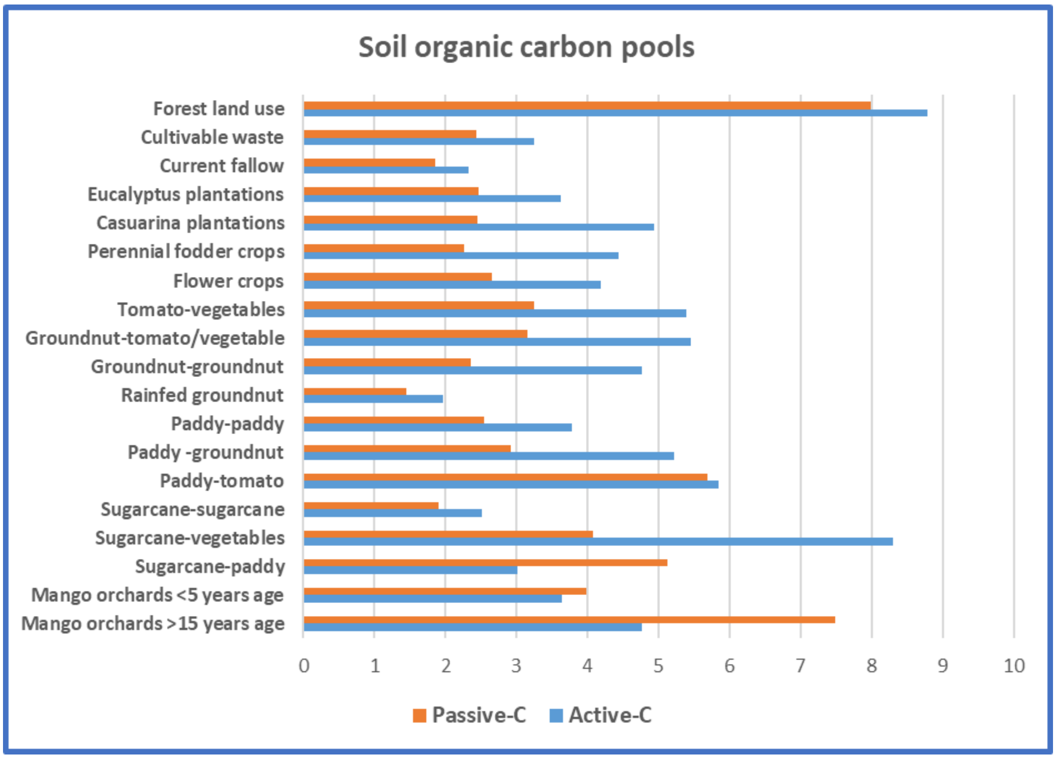

Figure 3. SOC pools distribution under different land use and cropping systems.

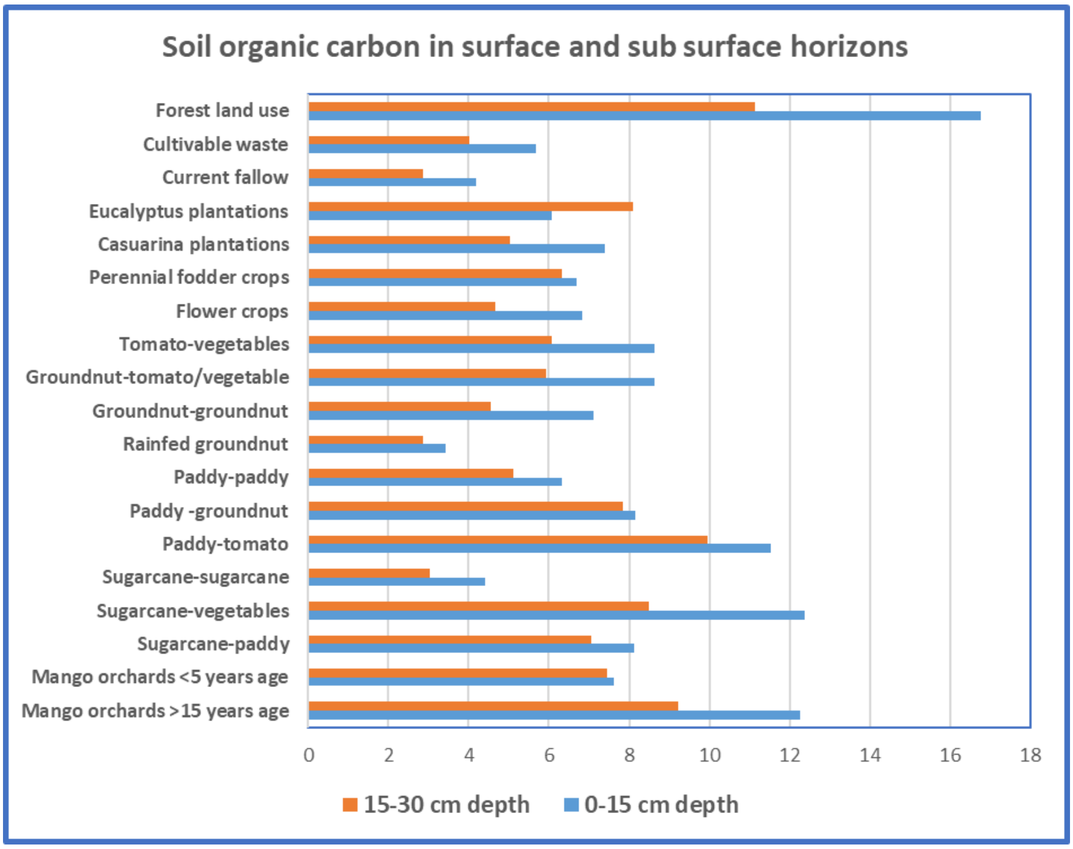

Figure 4. Depth-wise distribution of SOC content in different cropping systems and land use.

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systems, higher SOC stocks and pools were recorded in surface horizon (0-15 cm) followed by sub-surface horizon (Padbhushan *et al.*, 2016). The casuarina plantations had relatively higher active-C pool than eucalyptus plantations mainly because of relatively less decomposed leaf litter cover, which supports soil microbes. However, the eucalyptus plantations recorded high passive-C due to high lignin content of eucalyptus leaves. The depth-wise distribution of both carbon pools were relatively higher are higher in sub surface (15-30 cm) under eucalyptus plantations than casuarina plantations and *vice-versa*.

SOC Content and Carbon Farming Potential

The SOC content was significantly higher in surface (0-15 cm depth) than sub surface (15-30 cm depth) in all the cropping systems and land use systems of the study area (Turner *et al.*, 2003). The higher SOC in surface horizon was due to the addition of crop residues, organic manures, more root biomass, and root exudates. (Collins *et al.,* 2000). However, eucalyptus plantations recorded more SOC content in sub surface rather than surface horizon mainly because decomposed soil organic carbon moved to sub surface horizon due to coarse textured soils, and also more root biomass and exudates secretions in sub surface layers. The difference between surface and sub surface SOC content is larger under forest land use and tomato-vegetable cropping system due to addition of fresh organic carbon through leaf litter and FYM to surface horizon only and higher SOC stocks were recorded in surface and decreased with soil depth in all the land-use and cropping systems. Similar results were reported by Padbhushan *et al.* (2015) The SOC uniformly distributed in both depths under rainfed groundnut and mango orchards ≤ 5 years, may be due to less addition of organic carbon through organics.

The SOC content and carbon farming potential at 0-30 cm depth of different land use and cropping systems of the study area ranged from 3.14 and13.87 Mg ha^{-1} (lowest) to 13.96 and 62.19 Mg ha^{-1} (highest). The presence of highest SOC content and carbon potential ($P \leq 0.01$) under forest land use is due to higher organic matter addition through leaf litter (above the ground level) and live roots (below the ground level), which are relatively resistant to microbial oxidation. Hence, this forest land use system was considered as stabilized system with minimal disturbance (Nath *et al.*, 2018). Mango orchards ≥ 15 years recorded higher carbon farming potential followed by forest land use, mainly attributed to the year round addition of leaf litter fall, tree cover, and minimal disturbance to the soil resulting in decreased rate of microbial breakdown, especially during later stage with enrichment of lignin and hemi cellulose by soil microbes (Rumpel and Knabner, 2011). Of land use types studied, forest, mango orchards ≥ 15 years, and perennial forests exhibited highest SOC stocks (6.51-14.0 g kg^{-1}) in contrast with abandoned lands (3.52-4.85 g kg^{-1}). Similar kinds of results were reported by Zuazo *et al.* (2014) and established the relation between SOC stocks and land use types. The total soil organic carbon (10.74 g kg^{-1}) was three times higher than cultivated fallow. These results were in good agreement with the results reported by Naik *et al.* (2016) while studying SOC stocks in different orchards. The sugarcane-vegetables and paddy-tomato cropping systems reported on par carbon farming potential with mango orchards ≥ 15 years, mainly because of constant supply of easily decomposable organic manures and chemical fertilizers through integrated approach over a long period of time (Sollins *et al.,* 1996). Sugarcane-sugarcane cropping system had the lowest SOC stocks compared with other sugarcane based cropping systems of the study area, which might be due to frequent residue burning. Among the paddy based cropping systems of the study area, paddy-paddy recorded lowest SOC content and carbon farming potential compared to paddy-tomato and paddy-groundnut systems, because regular puddling favors the loss of aggregate associated carbon (Lal, 2004). The lowest SOC stocks were under rainfed groundnut mainly evidenced by no organic manure application, crop residues, and barren without adequate crop cover, and poor soil structure that might be the possible reasons for low carbon farming potential, on par with

Table 4. SOC content and carbon farming in 30 cm depth under different land use and cropping systems**.**

S No	Land use/Cropping system	SOC content (g kg^{-1})	Carbon farming potential (Mg ha^{-1})
1	Mango orchards ≥ 15 years age	10.74^{b}	46.04^{b}
2	Mango orchards ≤ 5 years age	7.55^{d}	34.32^{bcd}
3	Sugarcane-paddy	7.59^{d}	31.89^{cde}
4	Sugarcane-vegetables	10.44^{bc}	43.96^{bc}
5	Sugarcane-sugarcane	3.73^{gh}	17.15^{f}
6	Paddy-tomato	10.74^{b}	43.86^{bc}
7	Paddy -groundnut	7.99^{cd}	33.40^{cd}
8	Paddy-paddy	5.72^{defgh}	24.84^{def}
9	Rainfed groundnut	3.14^{fgh}	13.87^{ef}
10	Groundnut-groundnut	5.83^{defgh}	24.90^{def}
11	Groundnut-tomato/vegetable	7.28^{de}	30.12^{de}
12	Tomato-vegetables	7.35^{de}	30.30^{de}
13	Flower crops	5.74^{defgh}	25.49^{def}
14	Perennial fodder crops	6.51^{def}	27.80^{def}
15	Casuarina plantations	6.20^{defg}	25.68^{def}
16	Eucalyptus plantations	7.10^{def}	30.17^{de}
17	Current fallow	3.52^{h}	15.84^{f}
18	Cultivable waste	4.85^{efgh}	22.37^{def}
19	Forest land use	13.96^{a}	62.19^{a}
	F value	8.213**	7.301**
	P value	0.000	0.000

$^{a\text{-}h}$ Same set of alphabets indicates insignificant difference (Tukey's HSD).** Significant at 1% level.

current fallow lands. Cultivable waste lands had higher SOC stocks compared to current fallow lands, probably due to the increased fallowing of the land which leads to the accumulation of organic carbon through natural vegetative cover with no soil disturbances (Calegari *et al.* 2008) (Table 4). The carbon farming potential of cropping systems of the study area varies with the quantity of applied organic manures, adopted tillage practices, and relative clay content of soils, similar to results reported by Sokol *et al.* (2019).

CONCLUSIONS

The present study revealed that SOC pools and stocks were significantly influenced by the adopted land use and cropping systems. The active-C pool was significantly higher in forest land use, followed by sugarcane-vegetables. The passive-C pool was higher under forest land use, followed by mango orchards ≥ 15 years age, paddy-tomato, and sugarcane-paddy. The lowest active and passive-C pools were in rainfed groundnut, current fallow lands, and sugarcane-sugarcane cropping systems. The higher SOC status and carbon farming potential reported in forest lands and mango orchards ≥ 15 years age were followed by sugarcane-vegetables, and paddy-tomato systems and the lowest was under rainfed groundnut and sugarcane-sugarcane cropping systems. The cropping systems were grouped based on carbon farming potential: (1) High: mango orchards ≥15 years, sugarcane-vegetables, paddy-tomato and forest lands; (2) Medium: paddy–groundnut, groundnut-tomato/vegetable, tomato-vegetables, perennial fodders, casuarina and eucalyptus plantations and sugarcane-paddy; (3) Low: paddy-paddy, groundnut-groundnut, flower crops and cultivable wastes and, finally, (4) Very low: rainfed groundnut, current fallows, and sugarcane-sugarcane. The carbon farming potential of rainfed groundnut improved by application of manures, fertilizers, cover crops,

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Table 5. Grouping of different land use and cropping systems of the study area based on carbon farming potential.

S No	Very low	Low	Medium	High
1	Sugarcane-sugarcane	Paddy-paddy	Mango orchards 5 years age	Mango orchards ≥ 15 years age
2	Rainfed groundnut	Groundnut-groundnut	Sugarcane-paddy	Sugarcane-vegetables
3	Current fallow	Flower crops	Paddy -groundnut	Paddy-tomato
4		Cultivable waste	Groundnut-tomato/Vegetable	Forest land use
5			Tomato-vegetables	
6			Perennial fodder crops	
7			Casuarina plantations	
8			Eucalyptus plantations	

and stubble mulch. In sugarcane-sugarcane system, carbon farming potential improved by residue incorporation rather than residue burning. In paddy-paddy cropping system, carbon farming potential improved by introducing irrigated dry crops like maize in after harvest of paddy.. The carbon farming potential of cropping systems enhanced by addition of clay to the coarse textured soils with "tank silt" application.

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کاشت کربن و ذخایر کربن آلی خاک در کاربری های مختلف زمین و سامانه های زراعی در یک خاک آلفی سول

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چکیده

کمیّتِ ذخایرکربن آلی خاک (SOC) و توان کاشت کربن (carbon farming potential) درهر کاربری زمین تحت سامانه های زراعی متفاوت نشانگر مهمی از حاصلخیزی، سود دهی، و پایداری آن سامانه است. هدف این پژوهش ارزیابی پراکنش سطحی و عمقی ذخایر SOC (کربن فعالactive-C و غیر فعال passive-C) و توان کاشت کربن سامانه های زراعی عمده در خاک های آلفی سول در شرایط اقلیمی و زراعی جنوب منطقه اندراپرادش هندوستان بود. ما مقادیر کربن فعال ، غیر فعال، وSOC را در ۱۹ کاربری مختلف زمین تحت سامانه های زراعی متفاوت تعیین کردیم. نتایج حاکی از آن بود که بیشترین ( ) p<0.001وضعیت SOC و توان کاشت کربن در شرایط اراضی جنگلی بود (13.96 g kg^{-1} و 62.19 Mg ha^{-1}) و بعد از آن باغات مانگو (بادرختان ۱۵ ساله یا بیشتر) تقریبا ۲۳٪ کمتر، و همتراز با سامانه نیشکر–سبزیجات ۲۵/۲ ٪، و برنجکاری–گوجه فرنگی ۲۳/۱ ٪. کمترین مقادیر(p<0.001) SOC در سامانه بادام زمینی دیم برابر ۷۵٪ کمتر و بعد از آن سامانه نیشکر–نیشکر با ۷۳/۳ ٪ کاهش مشاهده شد. ذخیره کربن فعال در حد معناداری (p<0.001) در کاربری اراضی جنگلی بیشتر بود (8.79 g kg^{-1}) و بعد از آن سامانه نیشکر–سبزیجات (8.3 g kg^{-1}) قرار داشت. کربن غیر فعال در اراضی جنگلی به طور معناداری (p<0.001)بیشتر بود (برابر با 7.98 g kg^{-1}) همتراز با باغات مانگو با درختان ۱۵ ساله یا بیشتر 7.98 g)

kg^{-1}) و سپس سامانه برنجکاری-گوجه فرنگی (5.69 g kg^{-1}) و نیشکر-برنجکاری (5.12 g kg^{-1}). کمترین ($p<0.001$) میزان کربن فعال و غیر فعال در مزارع دیمکاری بادام زمینی، اراضی آیش، و سامانه نیشکر-نیشکر ثبت شد. در میان همه کاربری ها ی مختلف و سامانه های زراعی متفاوت که بررسی کردیم، توان کاشت کربن در اراضی جنگلی بیشتر بود و بعد از آن باغات مانگو با در ختان ۱۵ ساله، و سپس سامانه نیشکر-سبزیجات و برنجکاری-سبزیجات قرار داشت. این توان در سامانه های برنجکاری- بادام زمینی، بادام زمینی-گوجه فرنگی/ سبزیجات، گوجه فرنگی سبزیجات،مزارع چندساله علوفه کاری، اراضی زیر casuarina و اکالیپتوس، و سامانه نیشکر-برنجکاری در حد متوسط بود. نیز، در سامانه های برنجکاری-برنجکاری، بادام زمینی-بادامزمینی، گیاهان گل، و مناطق ضایعات قابل کشت توان مزبور کم بود و در سامانه بادام زمینی دیم، اراضی آیش، و نیشکر-نیشکر توان خیلی کم بود. به این قرار، پژوهش حاضر بر توان کاشت کربن تاکید میکند چرا که می توان آن را به عنوان نشانگر پایداری کاربری های گوناگون وسامانه های زراعی مختلف در شرایط اقلیمی-زراعی مناطق جنوبی قلمداد کرد.

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