Carbon stocks in major soil types and land-use systems in semiarid tropical region of southern India

K. Venkanna[1], Uttam Kumar Mandal[1,2,*], A. J. Solomon Raju[3], K. L. Sharma[1], Ravikant V. Adake[1], Pushpanjali[1], B. Sanjeeva Reddy[1], Rahul N. Masane[1], K. Venkatravamma[1] and B. Peda Babu[4]

[1]Central Research Institute for Dryland Agriculture, Hyderabad 500 059, India
[2]Present address: Central Soil Salinity Research Institute, Regional Research Station, Canning Town, South 24-Parganas 743 329, India
[3]Department of Environmental Sciences, Andhra University, Visakhapatnam 530 003, India
[4]Dr Y.S.R. Horticultural University, West Godavari 534 101, India

The present study was conducted to study the soil organic and inorganic carbon stocks under different land-use systems in Warangal district, Andhra Pradesh, representing semiarid tropical region of India. Results indicated that Vertisols and associated soils contained greater total C stocks, followed by Inceptisols and Alfisols. The soil organic carbon (SOC) stock was highest in Alfisols (52.84 Mg ha^{-1}) followed by Inceptisols (51.26 Mg ha^{-1}) and Vertisols and associated soils (49.33 Mg ha^{-1}), whereas soil inorganic carbon (SIC) stock was highest in Vertisols and associated soil (22.9 Mg ha^{-1}) followed by Inceptisols (17.5 Mg ha^{-1}) and Alfisols (12.4 Mg ha^{-1}). Among the different land-use systems, total C stock was highest in forest soils followed by fodder system, paddy, maize, cotton, redgram, intercrop, chilli, permanent fallow and lowest in castor system. Soil nitrogen also followed similar trend as SOC stock. Significant correlation ($P < 0.05$) was obtained between SOC stock and soil nitrogen with Mandal-wise annual rainfall. A surface map of soil C stock and soil N was prepared for Warangal district using kriging interpolation techniques and total C stock was estimated to 0.088 Pg out of which SOC stock was 77% and SIC stock was 23% for the district. A relationship was established between Walkey–Black Carbon and SOC estimated through dry combustion method using CN analyser and it was found that Walkley–Black carbon could recover 90% of SOC for semiarid tropical soils.

Keywords: Carbon sequestration, forest soils, land-use systems, organic carbon, soil types, total carbon stocks.

SOIL carbon is an important attribute of soil quality and its productivity. Soils are among the largest terrestrial reservoirs of carbon and hold potential for expanded C sequestration. Thus, they provide a potential way to reduce atmospheric concentration of carbon dioxide[1–3]. At the same time, this process provides other important benefits in terms of increased soil fertility and environmental quality. Small changes in the soil organic carbon (SOC) stock could result in significant impacts on the atmospheric carbon concentration[1–4]. The C balance of terrestrial ecosystems can be changed markedly by the impact of human activities, including deforestation, biomass burning and land-use change, which result in the release of trace gases that enhance the greenhouse effect[5–8]. Soil carbon pool comprises of two components: SOC and soil inorganic carbon (SIC). The SOC pool includes highly active humus to relatively inert charcoal C. The SIC pool includes elemental C and carbonate minerals (e.g. gypsum, calcite, dolomite, aragonite and siderite)[9,10].

Soils in tropical regions are low in SOC particularly those under the influence of arid, semiarid and sub-humid climates and this is a major factor contributing to their poor productivity[11,12]. Therefore, proper management of SOC is important for sustaining soil productivity and ensuring food security as well as protection from land degradation[13]. Maintaining or improving organic C levels in tropical soils is more difficult because of its rapid oxidation under prevailing high temperatures[14]. As lack of assured moisture does not support higher cropping intensity in this region, contribution of root biomass towards organic C is dismally low. Farmers in semiarid tropical regions do not use adequate and balanced amount of fertilizer nutrients because of uncertainty of rainfall, likely risk of failure of crops and poor economical condition which resulted in poor organic C status in those soils[15].

Despite the importance of soil carbon in terms of soil productivity and its impact on global C cycle, particularly in tropical ecosystems, there is lack of literature on systematic assessment of various components of soil carbon stocks in different land-use systems, as well as, in undisturbed state versus anthropogenically perturbed ecosystems[16]. Accurate assessment of the spatial pattern and stocks of soil carbon, especially at national and subnational scales, is an indispensable step when evaluating sequestration potential. Therefore, SOC stock inventories have been widely established at a global level[6], and in North America[17], South America[18], various European countries[19], India[7], Brazil[20] and China[21]. However, relatively little data are available on it, particularly in semiarid tropical regions[22] which have been regarded as major potential carbon sinks[23,24]. Furthermore, previous large-scale evaluations of SOC stocks in India have generally been based on decades-old information broad physiography or agro-ecological sub-region, which may have subsequently changed significantly and it was not possible to establish a baseline year. To better understand the SOC reservoir, it is necessary to update regional SOC information with intensive and contemporary measurements and to use a geostatistical method to avoid dependence on various maps having artificial boundaries.

*For correspondence. (e-mail: uttam_icar@yahoo.com)

Also wet oxidation by Walkley–Black method[25] is a routine, popular procedure for determination of soil organic C, but it is time-consuming and has a high potential to cause environmental pollution because of disposal of chromium and strong acids used in this analysis[26]. Around 60–86% of SOC was oxidized by Walkley–Black method and a correction factor was used to obtain the corrected SOC value. As the recovery percentage of carbon varies due to land use, texture and method of analysis, there was necessity to develop a relationship between SOC estimated through dry combustion in CN analyser and that estimated by Walkley–Black method for semiarid tropical region.

As systematic studies on assessment of carbon and nitrogen stocks in predominant soil types under different land-use systems in semiarid tropical regions were lacking, the present study was undertaken for Warangal district, Andhra Pradesh which represent the semiarid tropical environment. Using this database, a predictive model establishing a logical relationship between organic C estimated by CN analyser and that estimated by wet oxidation method using Walkley–Black procedure was also developed.

The present study was carried out in Warangal district, which is under agro-eco-sub-region (AESR) 7.2 (North Telangana Plateau; hot moist, semiarid eco-sub-region)[27]. The agroclimate of this subregion is characterized as hot, semiarid moist with dry summers and mild winters. The mean annual temperature varies from 25°C to 29°C. The mean summer (April–June) temperature varies from 32°C to 34°C, rising to a maximum of 39°C in May, and the mean winter (December–February) temperature varies from 20°C to 24°C. The mean annual rainfall varies from 700 to 1000 mm covering 42–45% of the mean annual potential evapotranspiration (PET) ranging between 1600 and 1800 mm. The southwest monsoon in the area breaks around the second–fourth week of June with 90% probability, and extends till the first week of October covering 85% of the mean annual rainfall. Mid-season agriculture drought is quite frequent in this Telangana zone. The area has an Ustic soil moisture regime. Around 60% of the net sown area of the district is under irrigation. Warangal district has considerable area under forest along with agriculture. Alfisols, Inceptisols, Vertisols and associated soils are dominant in the region.

Soil profiles were dug in all 51 Mandals of Warangal district, considering one profile in each Mandal. Soil samples were collected at every 20 cm depth interval up to a depth of 60 cm. In the present study, dominant land-use systems, viz. forest, fodder along with the agricultural systems were considered for sampling to know the variation of carbon stock in the region. The surface 60 cm soil depth was mostly affected by different land-management practices in cultivated fields and played an important role in carbon sequestration[28]; in our study up to 60 cm soil depth was considered. Soils were also collected from undisturbed permanent fallow (pristine) system to observe if there was any addition or depletion of soil carbon in the dominant cropping system of the region. For the estimation of bulk density, samples were collected separately for each soil depth. Both irrigated as well as rainfed system were considered for sampling for cultivated soils. Soil samples were collected in the period between harvesting and the next crop-growing season in order to avoid the direct effect of management practices during the crop-growing season. Information was collected from each soil profile site regarding their agriculture management practices such as crop rotation, tillage practices, fertilization, irrigation and crop yields (Table 1). A Global Positioning System (GPS) was used to identify the longitude, latitude and elevation of the site. The soil samples were analysed to know the carbon and nitrogen stock in different soil types and land-use system of the region.

Total C and N were measured using a CN analyser (Vario EL Cube, Elementar) adopting dry combustion technique. This method is based on the oxidation of organic C and thermal decomposition of carbonate mineral in a medium-temperature resistance furnace (~ 1000°C)[29]. A sample is placed in a tin sample capsule, crumpled to confine it and introduced into a quartz combustion reactor. Flash combustion occurs when a pulse of O_2 is injected into the quartz reactor shortly after introduction of the samples. Under these temperature and O_2 conditions, tin is oxidized to SnO_2 resulting in the increase of temperature to 1700–1800°C and the complete combustion of soil carbon and nitrogen. The combustion products (CO_2, N oxides and H_2O) are swept by the helium carrier gas and passed over CuO to convert any traceable CO to CO_2, and silver mesh to remove S and halogen gases. The gases then are flown through a heated Cu (650°C) column to remove excess oxygen and for the reduction of N oxides to N_2. The gas mixture is separated in its components via three columns by purge and trap chromatography and is subsequently detected by a thermal conductivity detector. Soil samples are also analysed for inorganic C titrimetrically by digesting them with dilute HCl (HCl C). The bulk density of soils is separately collected for each soil depth and is measured by soil core method.

The total organic carbon (CN analyser C – HCl C) is determined by subtracting inorganic carbon content from the CN analyser carbon content value. The carbon content for each layer is expressed as megagram per hectare[6] by multiplying carbon concentration (in fraction g/g) with bulk density (Mg m^{-3}) of each layer, thickness of the layer (in m) and the area of a hectare (in m^2). The summation for each layer in a profile depth will give total carbon (in Mg ha^{-1}). Organic C has also been determined by the Walkley–Black wet digestion method[25]. A surface map for soil carbon stock and total N is prepared for Warangal district using kriging interpolation techniques through Geostatistical wizard tool of Arc-GIS 10.1

Table 1. Land management practices followed in different cropping systems mentioned in the study (Warangal district, Andhra Pradesh)

Crop	Crop rotation	Tillage	Fertilization	Irrigation/ rainfed	Average yield (kg ha^{-1})
Paddy	Paddy–paddy	Summer ploughing, puddling and transplanting	FYM: 4–10 t ha^{-1} N: 80–120 kg ha^{-1} P: 26–30 kg ha^{-1}	Irrigated	5,290
Cotton	Cotton–fallow	Summer plouging, secondary tillage and seeding	FYM: 1–4 t ha^{-1} N: 60–150 kg ha^{-1} P: 40–80 kg ha^{-1} K: 80–120 kg ha^{-1}	Supplemental irrigation/rainfed	1,990
Fodder crop	Fodder crop	No tillage	N: 40 kg ha^{-1}	Irrigated	150,000
Castor	Castor–fallow	Summer ploughing and plough planting	FYM: 0–2 t ha^{-1} N: 25–60 kg ha^{-1} P: 10–30 kg ha^{-1}	Rainfed	1,290
Red gram or pigeon pea	Red gram–fallow	Summer ploughing and plough planting	FYM: 0–2 t ha^{-1} N: 40–60 kg ha^{-1} P: 10–40 kg ha^{-1}	Rainfed	820
Maize	Maize–fallow, maize–groundnut, maize–maize	Summer ploughing, secondary tillage and seeding	FYM: 2–10 t ha^{-1} N: 60–120 kg ha^{-1} P: 30–60 kg ha^{-1}	Rainfed/irrigated	5,960
Chilli	Chilli–chilli, Chilli–fallow	Summer ploughing, secondary tillage and seeding	FYM: 2–10 t ha^{-1} N: 60–120 kg ha^{-1} P: 30–60 kg ha^{-1}	Irrigated	5,812
Forest system	Tropical dry deciduous type of teak forests with bamboo, *Pterocarpus*, *Anogeissus*, *Buchanania*				

software (ESRI, Redlands, CA, USA) and organic, inorganic and total carbon stock of the district are evaluated.

Organic, inorganic and total C concentration (in %) and stocks (Mg ha^{-1}) under different land-use systems are presented in Table 2. Total C concentration is highest in forest soils followed by fodder system, paddy, red gram, cotton, maize, intercrop, chilli, permanent fallow and is lowest in case of castor system. The organic carbon concentration is also highest in forest system followed by fodder, paddy, maize, red gram, chilli, intercrop, cotton, permanent fallow and is lowest in case of castor system, whereas the inorganic carbon concentration is highest in cotton, intercrop, red gram, fodder, maize, permanent fallow, paddy, chilli, castor and is lowest in forest system.

Like organic carbon concentration, forest system (87.29 Mg ha^{-1}) shows the highest organic C stocks, followed by fodder (60.03 Mg ha^{-1}), paddy (57.12 Mg ha^{-1}), maize (52.12 Mg ha^{-1}), chilli (49.50 Mg ha^{-1}), red gram (48.44 Mg ha^{-1}), intercrop (45.69 Mg ha^{-1}), cotton (44.98 Mg ha^{-1}), permanent fallow (44.81 Mg ha^{-1}) and is lowest in case of castor (36.86 Mg ha^{-1}) system. Higher amount of organic carbon in forest system may be because of higher leaf litter and extensive root system of forest trees as well as zero perturbation and modification of hydrothermal regime in those soils. Fibrous root system of the grassland soils and no-till condition also increased the organic carbon stocks of these soils[30]. Srinivasarao *et al.*[31] also reported higher organic carbon content in a rice-based system at Ranchi (Jharkhand) and Phulbani (Odisha) sites. Higher enrichment of SOC in rice system has been ascribed to a number of factors, among which retardation of oxidation due to submergence, inclusion of extra C inputs through photosynthetic organisms and higher content of lignin and polyphenol content of rice crop residue which reduce the decomposition rate are important[32]. Cotton-based system on the other hand, shows the highest SIC stock (25.62 Mg ha^{-1}), whereas it is least in soils under forest and castor system.

For total carbon stock, highest amount has been recorded under forest system followed by fodder, paddy, maize, cotton, red gram, intercrop, chilli, permanent fallow and lowest under castor system. The percentage contribution of organic to total carbon stock is highest under forest system (90%) followed by castor, paddy, chilli, permanent fallow, fodder, maize, red gram, intercrop and lowest in case of cotton system. In case of castor both organic and inorganic C stocks are very low. The Walkley–Black C stock is marginally lower than the total organic

Table 2. Soil organic, inorganic and total carbon and Walkley–Black carbon stock in different land-use systems and soil types in Warangal district, Andhra Pradesh for 0–60 cm soil depth

Soil type and land-use system	Total inorganic carbon (HCl C) (%)	Total organic carbon (CN analyser – C–HCl C) (%)	Total carbon (CN analyser – C) (%)	Walkley–Black carbon (%)	Soil inorganic carbon stock (Mg ha^{-1})	Soil organic carbon stock (Mg ha^{-1})	Soil total carbon stock (Mg ha^{-1})	Soil Walkley–Black carbon (Mg ha^{-1})	Soil total N (%)
Castor	0.106	0.410	0.517	0.383	9.57	36.86	46.43	34.37	0.0542
Chilli	0.144	0.539	0.683	0.528	13.17	49.50	62.67	48.51	0.0721
Cotton	0.288	0.501	0.789	0.486	25.62	44.98	70.01	42.78	0.0650
Intercrop	0.241	0.512	0.753	0.492	21.69	45.69	67.77	43.26	0.0611
Permanent fallow (pristine soil)	0.160	0.490	0.650	0.446	14.67	44.81	59.49	40.71	0.0585
Fodder	0.236	0.675	0.911	0.617	20.72	60.03	80.75	57.20	0.0822
Forest	0.105	0.939	1.044	0.817	10.06	87.29	97.35	76.51	0.0877
Maize	0.202	0.575	0.777	0.535	18.16	52.12	70.28	48.53	0.0647
Paddy	0.159	0.642	0.801	0.576	14.97	57.12	72.09	49.87	0.0622
Red gram	0.236	0.554	0.790	0.508	20.51	48.44	68.96	44.48	0.0596
Irrigated	0.199	0.585	0.784	0.547	17.50	52.62	70.11	49.27	0.0696
Rainfed	0.195	0.527	0.722	0.484	17.47	46.89	64.36	43.070	0.0601
Cultivated	0.197	0.559	0.756	0.519	17.49	50.02	67.50	46.45	0.0648
Alfisol	0.125	0.610	0.736	0.561	12.39	52.84	65.24	51.61	0.0723
Inceptisol	0.209	0.565	0.774	0.523	17.47	51.26	68.73	48.41	0.0613
Vertisol and Vertic intergrade	0.256	0.579	0.835	0.517	22.93	49.33	72.26	43.94	0.0633

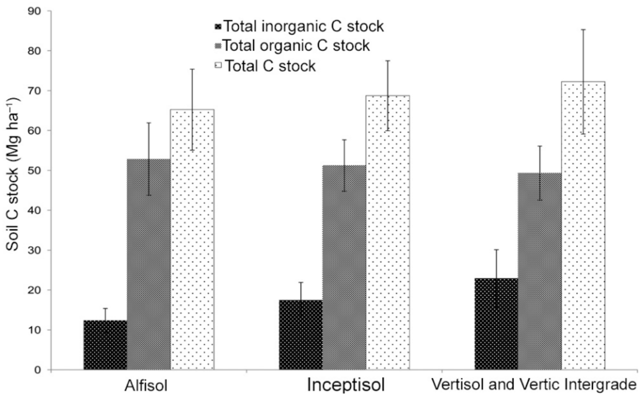

Figure 1. Distribution of carbon stock (total, organic and inorganic) in Alfisols, Inceptisols and Vertisols and associated soils for 0–60 cm soil depth.

carbon stock and follows similar trend like total organic carbon stock in case of different land-use systems. Irrigated system has more carbon stock than rainfed system.

In some of the dominant rainfed cropping systems of the region, like castor, there is reduction in organic carbon stock than in pristine permanent fallow lands. Supplementary irrigation and balanced fertilization improves the biomass production, including root of crop which ultimately improves the organic carbon stock of soils under arable irrigated systems.

In the study area, Vertisols and associated soils contain greater total C stocks, followed by Inceptisols < Alfisols (Table 2, Figure 1). In case of inorganic carbon concentration, it is greater in Vertisols and associated soils followed by Inceptisols and is lowest in Alfisols. However, organic C concentration is greater in Alfisols followed by Vertisols and Vertic Intergrade and is lowest in Inceptisols. In the study area, Vertisols and associated soils and few Inceptisols are calcareous, whereas Alfisols are mostly non-calcareous and most of the inorganic carbon is associated with calcium and magnesium carbonate. The higher organic carbon in Alfisols may be because large areas under Alfisols are also under forest cover which has very high SOC (0.6–1.09%, with a mean value of 0.939%).

The SOC stocks (CN analyser C – HCl C) ranges from 22.68 to 94.83 Mg ha^{-1} with a mean of 52.84 Mg ha^{-1} in Alfisols, 34.37 to 73.67 Mg ha^{-1} with a mean of 51.26 in Inceptisols and 27.80 to 74.20 Mg ha^{-1} with a mean of 49.33 Mg ha^{-1} in case of Vertisols and associated soils. The SIC ranges from 4.14 to 25.54 Mg ha^{-1} with a mean of 12.39 Mg ha^{-1} in Alfisols, 7.23 to 34.17 Mg ha^{-1} with a mean of 17.47 Mg ha^{-1} in Inceptisols and 9.08 to 71.78 Mg ha^{-1} with a mean of 22.93 Mg ha^{-1} in Vertisols and Vertic intergrade. In most of the cases, surface SOC is greater than deeper layers, whereas the reverse trend is observed for SIC in most of the cases. Total carbon stock ranges from 30.81 to 116.42 Mg ha^{-1} (mean 65.24 Mg ha^{-1}) in Alfisols, 43.12 to 107.20 Mg ha^{-1} (mean 68.73 Mg ha^{-1}) in Inceptisols and 39.39 to 145.98 Mg ha^{-1} (mean 72.26 Mg ha^{-1}) in Vertisols and associated soils. Ratio of organic to total carbon stock is maximum in Alfisols followed by Inceptisols and Vertisols.

Soil C content mostly depends on climate, soil type and land use. Srinivasarao *et al.*[22] also reported higher value of organic and inorganic carbon in Vertisols followed by Inceptisols, Alfisols and Aridisols in rainfed systems in

Table 3. Anova of regression model between Walkley–Black carbon and organic carbon measured through dry combustion using CN analyser

Model	Sum of square	*df*	Mean square	*F*	Significant level	Adjusted R^2	Standard error of estimate
Anova							
Regression	1.111	1	1.111	153.176	< 0.001	0.753	0.085
Residual	0.355	49	0.007				
Total	1.467	50					

Model	Unstandardized coefficients Beta	Standard error	Standardized coefficients Beta	*t*	Level of significance
Coefficients					
Constant	0.049	0.044	0.087	1.107	0.274
Walkley–Black carbon	1.019	0.082		12.376	< 0.001

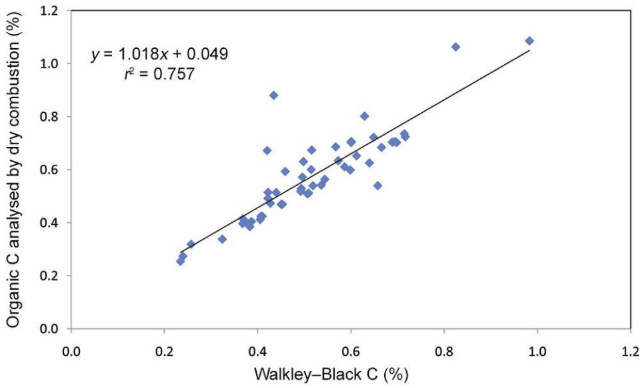

Figure 2. Relationship between Walkley–Black carbon and organic carbon analysed by dry combustion method using CN analyser.

tropical India. They recorded more inorganic C stock than organic C in case of Inceptisols and Vertisols, whereas it was reverse in case of Alfisols and Aridisols. We have observed relatively higher level of soil organic C stock than the inorganic C stock reported by Srinivasarao *et al.*[22] in their study in rainfed production systems of tropical India. The magnitude of inorganic carbon stocks in our study is relatively less than the stock reported by them.

Overall, the C concentrations reported from the Indian tropics are less than those reported in Australian soils[33–35]. Significantly lower levels of organic C in our soils could be attributed to high rates of oxidation of SOC resulting from high temperature in the tropics and frequent cultivation[36,37].

We have attempted to establish a relationship between Walkley–Black carbon content and total organic C analysed by subtracting total inorganic carbon from CN analyser carbon value (Table 3, Figure 2). The linear regression model indicated very good relationship with $r^2 = 0.753$ and standard error of estimation of 0.085. In our study Walkley–Black carbon extracts 90% of total organic carbon for soils of semiarid tropical regions. Instead of applying fixed correction factor, it is emphasized that appropriate correction factor needs to be developed for each region of Indian soils and adopted to increase the accuracy of estimating SOC stock and its dynamics.

Total soil N analysed using CN analyser varied between 0.024% and 0.129% with a mean value of 0.067%. The highest soil N of 0.129% is recorded under forest system in Alfisols at Khanapur Mandal of Warangal district. Among different land-use systems, total soil N is highest in forest system, followed by fodder, chilli, cotton, maize, paddy, intercrop, red gram, permanent fallow and is lowest in case of castor system. Among the arable crops, chilli, cotton and maize system record higher amount of soil N which also received higher amount of chemical N fertilizer. Soil N also follows a trend similar to SOC content in its distribution in three soil orders, and highest total soil N is found in Alfisols followed by Vertisols and Vertic Intergrade and lowest in case of Inceptisols. Total N is marginally higher in cultivated fields than in permanent fallow soils. Further, total N is higher in irrigated system than in rainfed condition. SOC and total nitrogen storage are also affected by land use in semiarid region of the Loess Plateau in China and natural grassland shows higher amount of total soil N and SOC storage than cropland[38].

On an average, total N : total C : total organic carbon and Walkley–Black carbon ratio for Warangal district are 1 : 11.5 : 8.7 and 7.8 respectively. In soil survey study, total soil N is considered one-tenth of SOC content in Indian soils, which slightly underestimates the value.

A surface map of soil C and total N has been prepared using kriging interpolation techniques. Ordinary kriging was used for the kriged map because it is the most commonly used type of kriging where the local mean of the random variable is unknown. No anisotropy was detected and isotropic semivariograms with rational quadratic, stable, rational quadratic and K-Bessel model were used for total soil carbon, SOC and SIC stocks, and soil N map respectively, as they give least root mean square error.

We have divided the soil total carbon stock into four categories; (I) < 55 Mg ha^{-1}, (II) 55–65 Mg ha^{-1}, (III) 65–75 Mg ha^{-1} and (IV) > 75 Mg ha^{-1} for 60 cm soil depth. The total carbon for Warangal district is estimated to be 0.088 Pg for 0–60 cm soil depth and the percentage contribution with grades I–IV accounts for 9.54, 16.32, 38.76 and 35.37 of the total soil area respectively (Figure 3).

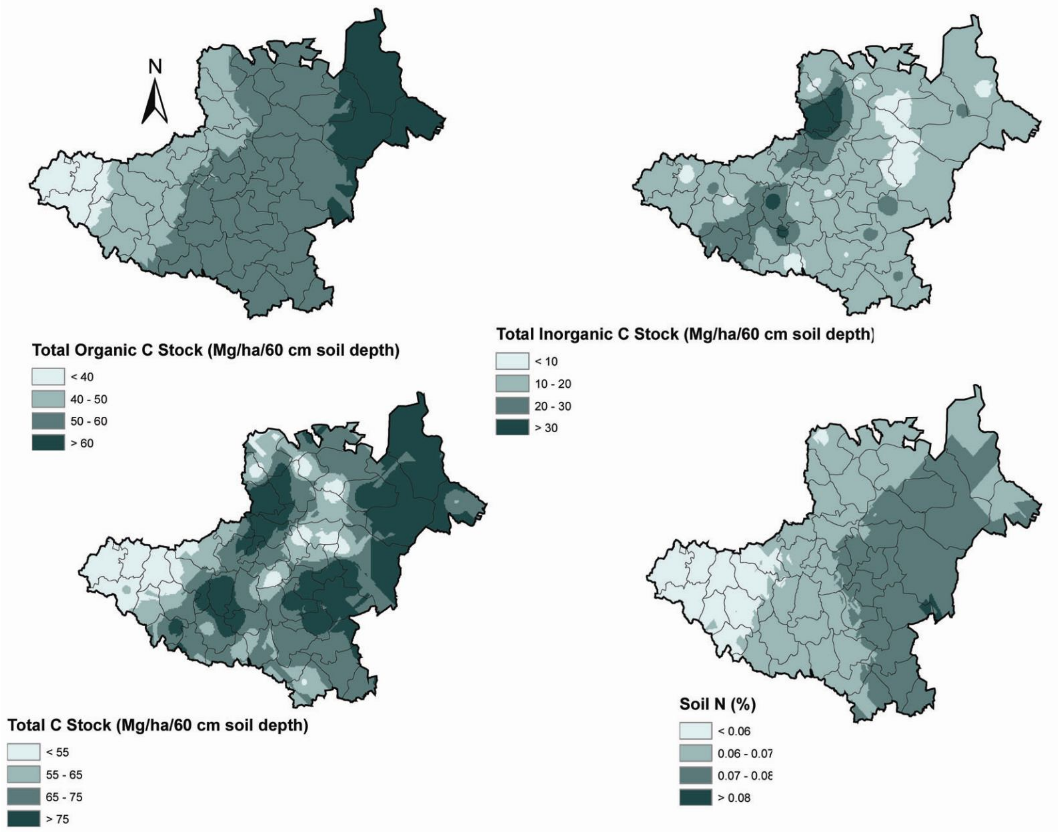

Figure 3. Kriged maps of soil carbon (organic, inorganic and total) stock and soil nitrogen for Warangal district.

The total organic carbon stock for Warangal district has been estimated as 0.068 Pg for 0–60 cm soil depth and the organic C stock with categories < 40 Mg ha^{-1}, 40–50 Mg ha^{-1}, 50–60 Mg ha^{-1} and > 60 Mg ha^{-1} are 5.19%, 20.36%, 57.92% and 16.53% respectively. For inorganic carbon stock it is estimated to be 0.02 Pg with categories < 10 Mg ha^{-1}, 10–20 Mg ha^{-1}, 20–30 Mg ha^{-1} and > 30 Mg ha^{-1} as 6.14%, 68.11%, 18.46% and 7.28% respectively, for 60 cm soil depth. Similarly, for total soil N concentration with categories < 0.06%, 0.06–0.07%, 0.07–0.08% and > 0.08% up to 60 cm soil depth are 16.33%, 46.97%, 36.37%, and 0.33% of the total soil area respectively. The western part of Warangal district is comparatively low in soil C stock and total N content. The total soil N for Warangal district is estimated as 0.00756 Pg for 0–60 cm soil depth. At the national level, a total of 24.3 Pg of SOC has been estimated for a total of 229 m ha of Indian soils[7]. If the values obtained in the cited studies and those which we have obtained are accurate, SOC stocks of Warangal district which covers nearly 0.39% area of the country contribute 0.36% of the National SOC stock up to 60 cm soil depth.

We have also attempted to establish a relationship between SOC stock in each Mandal of Warangal district and Mandal-wise mean normal annual rainfall (mm). Significant positive correlation ($P < 0.05$) has been obtained between SOC stock and mean annual rainfall ($r = 0.436$, Figure 4). Soil N is also positively correlated with Mandal-wise normal rainfall. On the other hand, SIC stocks decrease with the increase in mean annual rainfall ($r = -0.10$). In our study, percentage of soil clay is well correlated with total inorganic carbon ($r = 0.462$), but there is no relationship with organic carbon content. Calcium carbonate is a common mineral in soils of the dry regions of the world, stretching from sub-humid to arid zones, as soils of these regions are calcareous in nature[9]. Further, SIC pool consists of primary inorganic carbonates or lithogenic inorganic carbonates and secondary inorganic carbonates[9]. The reaction of atmospheric CO_2 with water (H_2O) and calcium (Ca^{2+}) in the upper horizons of the soil followed by leaching into the subsoil, and subsequent reprecipitation result in the formation of secondary carbonates in the deeper layer of the profile and sequestration of atmospheric CO_2. Yield is also positively correlated with organic carbon stock ($r = 0.256$).

We have also tried to develop a relationship between input of SOC with SOC stock. The input of SOC has been estimated based on biomass yield, input of organic residue, including FYM, fertilizers and leaf fall to soils. The input of organic matter is also well correlated with organic carbon stock ($r = 0.732$) (Figure 5).

To know the maximum amount of carbon the soil can hold or to know the carbon saturation level of the soil, a steady state SOC concentration (C_t), has an asymptotic

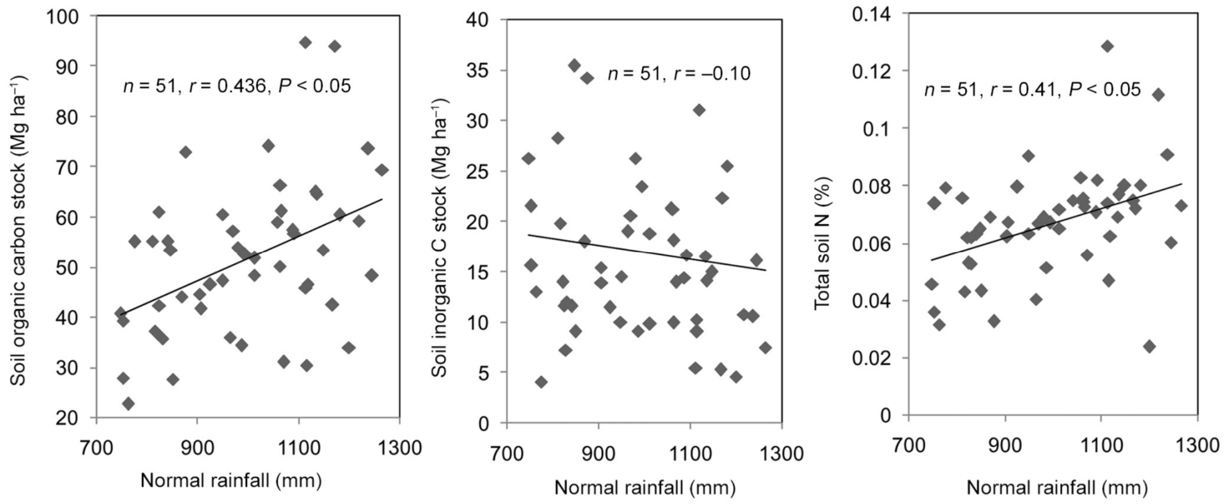

Figure 4. Relationship between Mandal-wise mean annual rainfall and soil inorganic and organic carbon stock and soil nitrogen.

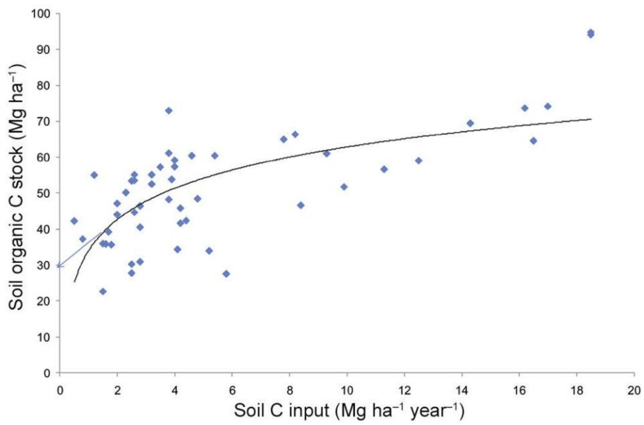

Figure 5. Soil organic carbon stock (Mg ha^{-1}) expressed as a function of carbon input levels (Mg ha^{-1} $year^{-1}$) for the semiarid tropical region of South India.

relationship between C inputs (I) and the maximum amount of C in a given soil (C_m)[39]

$$C_t = I/(k + I/C_m),$$

where C_m is the maximum amount of C in a given soil. As a soil approaches C saturation level, the proportion of new C input stabilized by physico-chemical mechanisms is reduced by the proportion of SOC present. Most current SOC models employ first-order kinetics for decomposition processes, and therefore, show linear relationship between C input level and SOC level at equilibrium (i.e. steady-state). However, in long-term agro-ecosystem, experiments show little or no change in SOC stocks in response to varying C input levels. This lack of response in SOC levels to varying levels of C input, over many years and the apparent dependency between C stabilization efficiency and soil C content, suggest the possibility of an upper limit of saturation level for the soil carbon in different soil types and regions. The C saturation level in the soil of semiarid tropics is estimated to be 73.21 Mg ha^{-1} up to 60 cm soil depth.

Vertisols and associated soils have relatively greater total soil carbon stock than other soil types, whereas soils of regions with less rainfall show larger inorganic C content than those of regions with more rainfall. Amount of rainfall is significantly related with the amount of organic C stocks as well as soil N. Irrigated agricultural systems with balanced fertilizer application are characterized by higher soil organic stock than areas where rainfed subsistence agriculture is practised. Some of the permanent fallow areas have better SOC than fields under monocrop castor system. Our results present a large-scale overview of the present soil carbon density in different land-use and soil types across the Warangal district, a representative district of semiarid tropical region of India. It is probable that the potential for further carbon sequestration is high under all land-use types. It is also possible that additional appropriate management practices, such as soil fertilization, erosion control and artificial fencing for forestland and grassland and the use of mulches, conservation tillage, and application of organic and green manure for cropland would enhance SOC sequestration in the region.

Managing SOC is central for sustainable land management because soil organic matter influences numerous soil properties relevant to ecosystem functioning and crop growth. One of easy ways for C enrichment in the soil is incorporation of crop residue or organic amendments such as FYM, livestock excreta, green manure, compost, vermicompost, farm waste, etc. along with minimum or no tillage practices. This could have long-term consequences in sustaining natural resources. The data presented support that a regular input of biomass-C along with chemical fertilizers is essential to improve SOC in the semiarid tropics of India, and for minimizing the depletion of SOC stock under continuous cropping. However, availability of FYM is a major challenge. Large amount of city wastes, including municipal solid wastes being produced and left almost unused may be a viable option. The relationship between Walkley–Black carbon and dry combustion carbon will help develop baseline data for soil organic carbon stock and to monitor its changes under long-term land-management treatments.

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