Soil Carbon Sequestration Strategies in Rainfed Agriculture

Chapter · November 2011

8 authors, including:

Srinivasrao Ch.
National Academy of Agricultural Research Management

Sumanta Kundu
Central Research Institute for Dryland Agriculture, India

Vijay Jakkula
Sehgal Foundation

Sharan Bhoopal Reddy
University of Agricultural Sciences, Raichur

Soil Carbon Sequestration Strategies in Rainfed Agriculture

Ch Srinivasarao, Sumanta Kundu, Vijay Sandeep Jakkula, Sharan Bhoopal Reddy, R. Prakash Naik, V. Rupendra Manideep and K. Veeramani

Central Research Institute for Dryland Agriculture,
Santoshnagar, Saidabad (P.O.), Hyderabad, 500 059, Andhra Pradesh

To counter the adverse effects of climate change and global warming is an urgent need especially in view of the targets set by India for the reduction of CO_2 emissions of its gross domestic product by 20-25% by 2020, below 2005 levels. In the light of this, the endeavor to enrich soil organic carbon (SOC) stocks by sequestering atmospheric carbon is crucial and so too is the need to understand soil health and crop productivity under different management strategies. Optimum levels of SOC can be managed through the adoption of appropriate crop rotation (Wright and Hons, 2005), fertility management, using inorganic fertilizers and organic amendments (Schuman *et al*., 2002; Mandal *et al*., 2007; Majumder *et al*., 2008) and tillage methods (Lal, 2009). Soils in rain-deficit environments of the tropical, sub-tropical regions are inherently low in SOC, and agronomic yield is related to soil quality. Therefore, reversing the declining trend of SOC stock is essential to enhancing agronomic productivity through balanced application of plant nutrients (i.e., N, P, K, S, Zn, Mo). Crop cultivation adversely affects the distribution and stability of soil aggregates and reduces SOC stock in soils (Kong *et al*., 2005). The magnitude of reduction in SOC due to cropping, however, varies depending upon the climatic conditions and intensity of cropping (Lal, 2004). The rate of decomposition/ mineralization of SOC stock is generally higher in the tropics than in temperate regions (Jenkinson and Ayanaba, 1977). Nonetheless, crop species also play an important role in maintaining SOC stock through differences in quality and quantity of the residues returned, which determine the mean residence time (MRT) of SOC (Mandal *et al*., 2007). Once the pathways of carbon sequestration in soils are identified, suitable agricultural strategies may be developed that have the potential to improve SOC stocks and thus attenuate CO_2 loading into the atmosphere and curb global warming (Lal, 2009). Most of the research so far on C sequestration in agricultural soils is confined to temperate regions while little information is available from tropical and subtropical countries including India (Velayutham *et al*., 2000; Lal, 2004). In India, C sequestration was studied only under irrigated conditions till now. There has been no study in semiarid rainfed conditions, where water stress, high temperature and low biomass are common features. Most of the crop management impact studies on soil carbon sequestration are limited to only surface (0.15 m) or root zone (Paustian *et al*., 1997).

Rainfed croplands cover 1.132 billion ha and meet about 60 % of the food and nutritional needs of the world's population (Biradar *et al*., 2009). The USA, Russia, China, Brazil and India, account for the highest rainfed cropland areas in the world. Rainfed agro-ecosystems occupy a considerable place in Indian agriculture, covering 80 million ha, in arid, semi-arid and sub-humid climatic zones; constituting nearly 57% of the net cultivated area. In India, soils under rainfed agriculture are categorized by low SOC and N concentrations in most agro-ecoregions. The data on SOC concentrations determined in 21 locations in 1.05-m deep profile across rainfed regions of India, covering eight production systems, showed that these soils are low in C concentration (<5 g kg^{-1}) and stocks (20 to 97 Mg ha^{-1}) (Srinivasarao *et al*., 2009). Maintaining soil and crop productivity in the long term under continuous cropping is the major challenge in rainfed regions of India. Low crop yields, low or no biomass residue, coupled with long fallow periods which extend up to to 7 months in the year, result in adverse environments that do not sustain soil SOC levels. The magnitude of decline or enhancement of SOC due to continuous cultivation depends on the balance between the loss of carbon by oxidative forces during tillage; the quantity and quality of crop residues that are returned, and the organic amendments added to the soils. Therefore, crop and soil management practices have to be tailored to ensure long term crop/cropping systems. The use of plant nutrients and organic amendments, and the inclusion and cultivation of legumes, support SOC build up in soil. Crop residues are used for many purposes in India, and therefore not always available for agriculture due to competing alternate uses.

In the present study, in the semi arid and sub-humid tropical conditions of India, different rainfed production systems were observed; the effects of 13-27 years of chemical fertilization and the use of crop residue/ green leaf manuring/ FYM on SOC sequestration in different soil types were investigated in long term manurial trials and the requirement of critical carbon inputs for zero change in C levels were calculated.

Study Area and Treatmental Details

The study area includes the experimental sites of the long-term experiments on permanent manurial trials/ integrated nutrient management in progress at network centers under All India Coordinated Research Project on Dryland Agriculture (AICRPDA) at 6 locations, viz., Anantapur, Bangalore, Solapur, Indore, Sardar Krishinagar and Varanasi. While selecting the locations, variability in soil types and production systems have been taken into consideration.

For the present investigation, in each Permanent Manurial Trial (PMT), some selected treatments were chosen to answer some specific questions like whether continuous cropping and long term application of fertilizer in conjunction with organic material, viz., FYM, ground nut shell, crop residue or subabul leaves can sequester soil organic carbon and other macro and micro nutrients in arid, semi arid and sub humid environment, and whether the above mentioned organic materials can be substitutes in case of sub-optimal application of NPK fertilizer for sustaining productivity.

Table 1 : Details of location, soil type and production system included in the present study.

AICRPDA Centre	Production system based	State	Latitude, Longitude and Altitude	Soil type	Climate	Average Annual Rainfall (mm)
Anantapur	Groundnut	Andhra Pradesh	14°42’ N, 77°40’ E, 350 m	Alfisols	Semi-arid	566
Bangalore	Finger millet	Karnataka	12°46’ N, 77°11’ E, 810m	Alfisols	Semi-arid	768
Solapur	Rabi Sorghum	Maharashtra	17°51’N, 75°32’E, 480m	Vertisols	Semi-arid	723
SK Nagar	Pearl millet	Gujarat	24°30’N, 72°13’E, 152.5m	Entisols	Semiarid	550
Indore	Soybean	Madhya Pradesh	22°51’N, 75°51’E, 530m	Vertisols	Semi-arid	1000
Varanasi	Rice	Uttar Pradesh	25°11’N, 82°51’E, 480m	Inceptisols	Sub-humid	1080

Source : Srinivasarao *et al* (2009)

Table 2 : Selected carbon management options for different rainfed production systems in permanent manurial trials in the studied locations

Production systems/ Location	Crop/crop sequence	Duration/No. of years of permanent manurial trial	Treatment details
Groundnut based production system (Anantapur)	Groundnut monocropping	1985-2005 (20 years)	T1-Control (no fertilizer), T2-100% recommended dose of fertilizer (RDF) (20:40:40 N, P_2O_5, K_2O), T3-50% RDF+ 4 Mg groundnut shells (GNS) ha^{-1}, T4-50% RDF+ 4 Mg FYM ha^{-1} T5-100% organic (5 Mg FYM ha^{-1}).
Fingermillet based production system (Bangalore)	Groundnut-Fingermillet and Fingermillet-Fingermillet rotation	1978-2005 (27 years)	T1-Control T2-FYM @ 10 Mg ha^{-1} T3-FYM@ 10 Mg ha^{-1}+ 50 % NPK T4-FYM@ 10 Mg ha^{-1}+100 % NPK T5-Rec.NPK (25:50 : 25 kg NPK ha^{-1} – groundnut; 50: 50:25 kg NPK ha^{-1} – fingermillet)
Rabi sorghum based production system (Solapur)	Sorghum	1985-2006 (21 years)	T1-Control T2-25 kg N ha^{-1} –Urea T3-50 kg N ha^{-1} – Urea T4-25 kg N ha^{-1} –Crop residue (CR) T5-25 kg N ha^{-1} – FYM T6-25 kg N ha^{-1} -CR+25 kg N ha^{-1}-Urea T7-25 kg N ha^{-1} -FYM+25 kg N ha^{-1}-Urea T8-25 kg N ha^{-1} -CR+25 kg N ha^{-1}-*Leucaena* T9-25 kg N ha^{-1} – *Leucaena* T10-25 kg N ha^{-1} -*Leucaena* +25 kg N ha^{-1}-Urea
Pearlmillet based production system (S.K. Nagar)	Pearlmillet-clusterbean-castor rotation (once in every three years)	1988-2006 (18 years)	T1-Control; T2-100% recommended dose of N through mineral fertilizer (RDNF); T3-50% RDNF; T4-50% recommended N (FYM); T5-50% recommended N (fertilizer)+50% recommended N (FYM); T6 –Farmers method (5 Mg of FYM ha^{-1} once in 3 years)
Soybean based production system (Indore)	Soybean-safflower	1992-2007 (15 years)	T1-Control; T2-20 kg N+ 13 kg P; T3-30 kg N+ 20 kg P; T4-40 kg N+ 26 kg P; T5-60 kg N+ 35 kg P; T6-FYM 6 Mg ha^{-1}+ 20 kg N, 13 kg P; T7-Soybean residue 5 Mg ha-1+ 20 kg N, 13 kg P; T8-FYM@6 Mg ha^{-1}; T9-Crop residues of Soybean @ 5 Mg ha^{-1}.
Rice based production system (Varanasi)	Rice-lentil	1986-2007 (21 years)	T1-Control; T2-100% RDF (inorganic); T3-50% RDF (inorganic); T4-100% organic (FYM); T5-50% organic (FYM); T6-50% RDF+ 50%(foliar); T7-50% organic (FYM)+ 50%RDF; T8-Farmers practice

Source : Srinivasarao *et al* (2009)

Soil Carbon Sequestration in Different Rainfed Production Systems

Groundnut based system

Total SOC stock of the profile was also significantly ($P<0.05$) improved, and the highest stock was measured in 50% RDF + 4 Mg ha^{-1} GNS (47.2 Mg C ha^{-1}) followed by 50% RDF + 4 Mg ha^{-1} FYM (45.9 Mg C ha^{-1}), 5 Mg ha^{-1} FYM (42.4 Mg C ha^{-1}), 100% RDF (36.2 Mg C ha^{-1}) and the lowest in the control (32.2 Mg C ha^{-1}) (Srinivasarao *et al*., 2011a) (Fig. 1). The application of 50% RDF + 4 Mg ha^{-1} GNS registered the highest SOC build up (46.6%) followed by that in 50% RDF + 4 Mg ha^{-1} FYM (45.9%), 5 Mg ha^{-1} FYM (31.7%) and the lowest in 100% RDF (12.4%) compared with control (Fig. 1a). The SOC build up rate over 20 years of cropping also followed a similar trend, with the highest rate in 50% RDF + 4 Mg ha^{-1} GNS (0.750 Mg C ha^{-1} yr^{-1}) and the lowest in 100% RDF (0.200 Mg C ha^{-1} yr^{-1}). This build up of SOC in different amendments is proportional to the total C inputs viz., 100% RDF (1051 kg vs. 505 kg ha^{-1} in control), 50% RDF+ 4 Mg ha^{-1} GNS (3461 kg C vs. 505 kg), 50% RDF + 4 Mg ha^{-1} FYM (2964 kg vs. 505 kg), and 5 Mg ha^{-1} FYM (2578 kg vs. 505 kg). Total C input was significantly correlated with the profile mean SOC concentration (R^2=0.99; $P<0.05$), SOC stocks in the profile (R^2=0.48; $P<0.05$) explaining 99 and 48%, respectively, of the total variability. Similarly, total SOC sequestered over 20 years was strongly correlated with total C inputs (R^2=0.98; $P<0.05$), explaining 98% of the variability in C sequestered. A higher C retention in manure-amended than in other plots was probably because the manure was partly decomposed and contained a higher proportion of chemically recalcitrant organic compounds (Paustian *et al*., 1992).

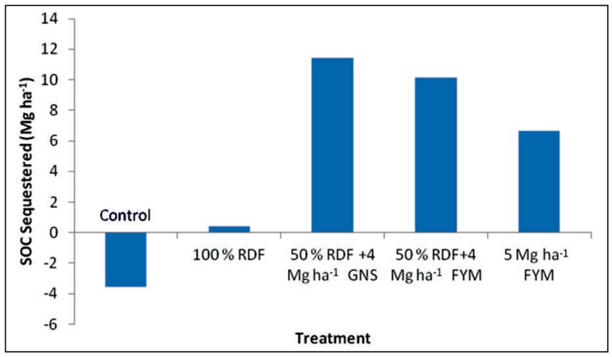

Fig. 1a. SOC sequestration in the profile under different fertilization treatments over 20 years in groundnut monocropping system under semiarid conditions.

Fingermillet based system

Profile SOC stock was highest in the FYM 10 Mg ha^{-1}+100% NPK (85.7 Mg C ha^{-1}) followed by FYM 10 Mg ha^{-1}+50% NPK (81.6 Mg C ha^{-1})> FYM 10 Mg ha^{-1} (79.1 Mg C ha^{-1})> NPK (70.5 Mg C ha^{-1}) and control (63.5 Mg C ha^{-1}) treatments (Srinivasarao *et al*., 2011b) (Fig. 2). Higher percentage of C buildup was observed with FYM 10 Mg ha^{-1}+100% NPK treatment (41.2%) followed by FYM 10 Mg ha^{-1}+50% NPK treatment (36.2%) which reflected in

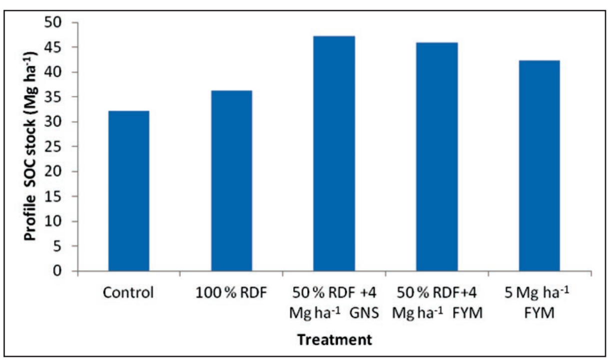

Fig. 1. Profile SOC stock under different fertilization treatments over 20 years in groundnut monocropping system under semiarid conditions.

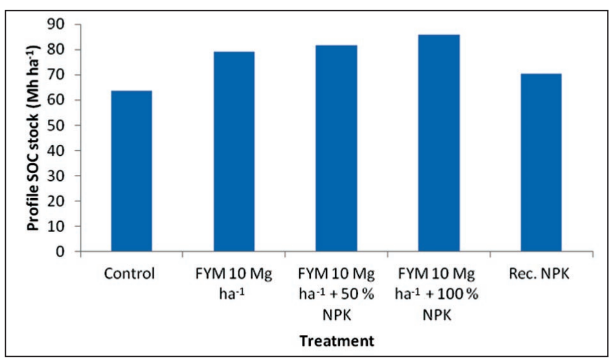

Fig. 2. SOC stock in soil profile as affected by 27 years of fingermillet-fingermillet cropping and fertilization under semiarid conditions

the profile SOC of respective treatments (Fig. 2a). C buildup rate also followed similar trend as C buildup. According to our calculation 27.7% C was stabilized from external input in the form of FYM. In all the treatments except control, there was a sequestration of organic carbon ranging from 0.2 to 15.4 Mg ha^{-1}. Higher C sequestration was observed with the application of FYM alone or along with 100% and 50% recommended NPK. Cultivation of crop as such without using any organic and/or inorganic fertilizer inputs (control) caused a net depletion of 6.8 Mg C ha^{-1}, whereas recommended dose of NPK maintained the initial SOC stock.

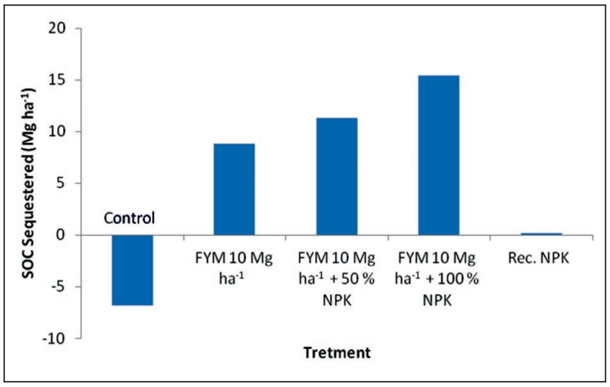

Fig. 2a. SOC sequestration in soil profile as affected by 27 years of fingermillet-fingermillet cropping and fertilization under semiarid conditions

The carbon stock of the profile showed a highly significant correlation with cumulative crop residue (r=0.95; P<0.05), external (FYM) (r=0.92; P<0.05) and total C inputs (r=0.96; P<0.05) explaining 85-92% variability. C buildup also significantly related with cumulative crop residue (r=0.89; P<0.05), external (FYM) (r=0.96; P<0.05) and total C inputs (r=0.98; P<0.05) explaining 79-96 % variability. A positive relationship between the crop residue C, external C, and the total carbon impact with the total organic carbon in the profile, indicated that the carbon input positively influences carbon stock in the soil, as well as C build up percentage.

Groundnut-fingermillet system

There were significant differences in the profile SOC stock among treatments (P<0.05 (Fig. 3). The SOC stock was the highest in the FYM +100% NPK (73.0 Mg C ha^{-1}), and it was on par with FYM +50 % NPK (72.9 Mg C ha^{-1})> FYM (69.4 Mg C ha^{-1})> NPK (63.3 Mg C ha^{-1}) > control (51.7 Mg C ha^{-1}) treatments (Srinivasarao *et al*., 2011c). A higher percentage of C buildup was observed FYM +100% NPK treatment (41.2%) followed by FYM +50% NPK treatment (41.0%), which reflected in the profile SOC concentration of respective treatments (Fig. 3a). The SOC buildup rate also followed a similar trend as C buildup. The C budgeting show that 36.8% of the C applied as FYM was stabilized. With the exception of control and sole application of NPK through chemical fertilizer, from the magnitude of SOC sequestration in other treatments was 5.7 to 9.3 Mg ha^{-1}. Higher SOC sequestration was observed with

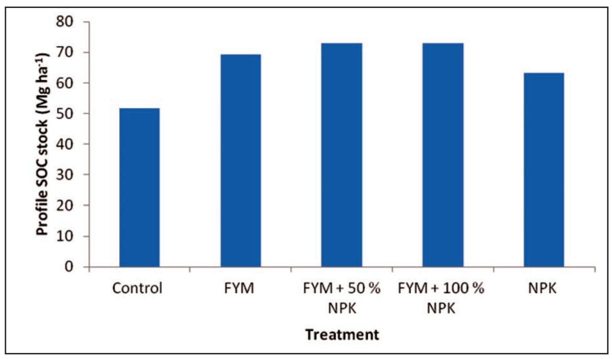

Fig. 3. SOC stock in soil profile as affected by 13 years of groundnut-fingermillet cropping and fertilization under semiarid conditions

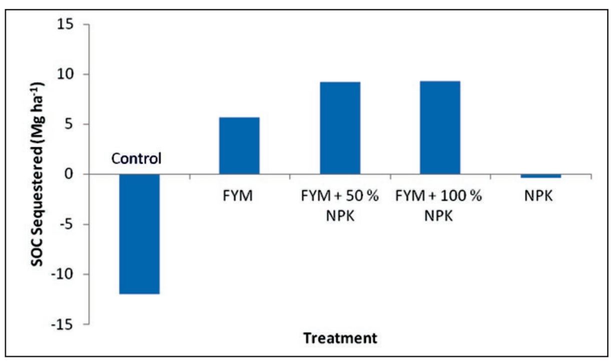

Fig. 3a. SOC sequestration in soil profile as affected by 13 years of groundnut-fingermillet cropping and fertilization under semiarid conditions.

the application of FYM alone or along with 100% and 50% recommended rate of NPK. Cultivation of a crop without using any organic and/or inorganic fertilizer inputs (control) caused a net depletion of SOC stock by 12.0 Mg C ha^{-1}. In comparison, use of NPK maintained the SOC stock.

Annual inputs of C in terms of crop residues and application of FYM significantly affect C buildup and C stock of the profile. An asymptotic relationship was observed between SOC stock and input of C through different treatments. Application of FYM (10 Mg ha^{-1}) with 50% or 100% recommended dose of NPK over 13 years of cropping enhanced buildup of SOC over control. The buildup of C was the highest in FYM +100% NPK treatment (41.2%), and was on par with FYM +50% NPK (41.0%)> FYM (34.2%) > NPK (22.4%) treatments. The rate of C buildup also followed a similar trend.

Rabi sorghum based system

The profile SOC stock differed significantly ($P<0.05$) among treatments. The highest SOC stock of 68.5 Mg C ha^{-1} was observed in the 25 kg N (CR)+25kg N (*Leucaena*) followed by that of 65.8 Mg C ha^{-1} in the 25 kg N (CR)+25kg N (urea) >that in the 25 kg N (FYM)+25 kg N (urea) (62.6 Mg C ha^{-1})> 50 kg N (urea) (54.1 Mg C ha^{-1})= 25 kg N (*Leucaena*)+25kg N (urea) (53.4 Mg C ha^{-1}), and the lowest (49.0 Mg C ha^{-1}) in the control (Srinivasarao *et al*., 2011d) (Fig. 4). Relatively higher percentage of SOC sequestration was observed in the 25 kg N (CR)+25kg N (*Leucaena*) treatment (39.8%) followed by 25 kg N (CR)+25kg N (urea) (34.3%) and 25 kg N (FYM)+25 kg N (urea) (27.8%) (Fig. 4a). The rate of SOC sequestration also followed a trend similar to that of SOC sequestration. The data show that 32.6, 28.2 and 22.6% of biomass C input was stabilized in FYM, sorghum CR and *Leucaena* clippings, respectively.

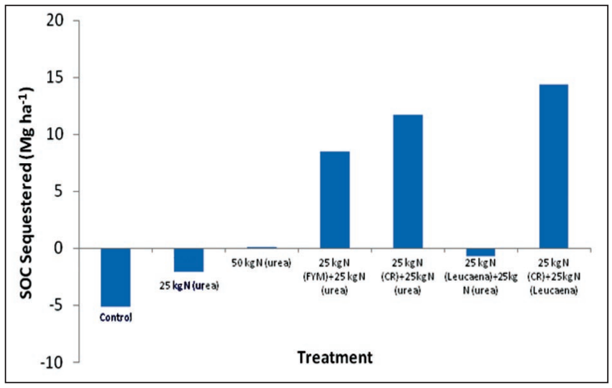

Fig. 4a. SOC sequestration for different fertilization treatments in 22 years of rabi sorghum cropping under semiarid conditions

Pearlmillet based System

The highest rate of SOC buildup from the C inputs was observed in the treatment involving the application of 50% RDN (F) + 50 % RDN (FYM) (42.5 %) followed by that in the 50 % RDN (FYM) (30.7%), farmer's practice (10.6%), 100 % RDN (F) (7.8%) and the lowest 50% RDN (F) (7.3%) which was also reflected in the profile SOC stock in the

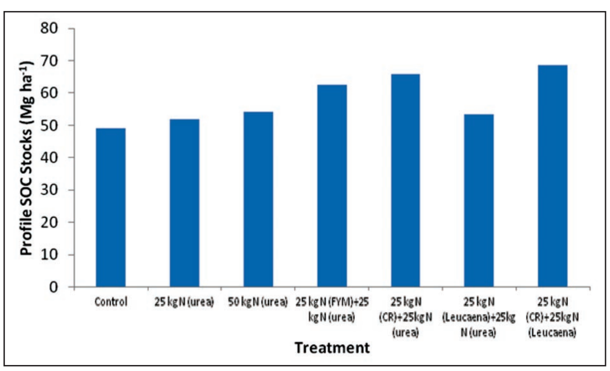

Fig. 4. Profile SOC stock for different fertilization treatments in 21 years of *rabi* sorghum cropping under semiarid conditions

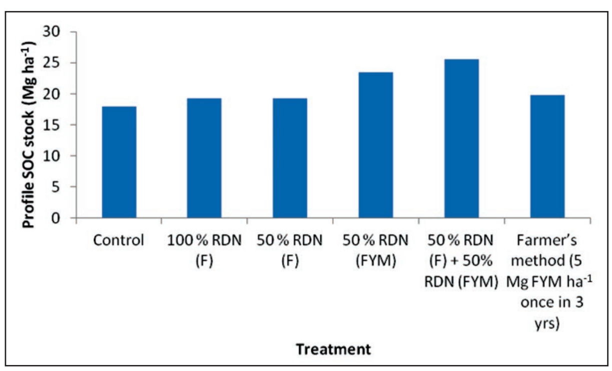

Fig. 5. Profile SOC stock affected by 18 years of pearlmillet-clusterbean-castor cropping and fertilization under semiarid conditions.

respective treatments (Srinivasarao *et al*., 2011e) (Fig. 5). The rate of SOC buildup also followed a trend similar to that of SOC buildup. The mean rate of SOC buildup during the 18 years of cropping was the highest in 50 % RDN (F) + 50 % RDN (FYM) (0.422 Mg C ha^{-1}) and the lowest in 50% RDN (F) (0.072 Mg C ha^{-1}) (Fig. 5a). It was estimated that 23% of applied C through FYM was stabilized, and the rest (77%) was lost through oxidation. The SOC stock was depleted in all treatments, and the highest magnitude of depletion of 12 Mg C ha^{-1} was observed in the control.

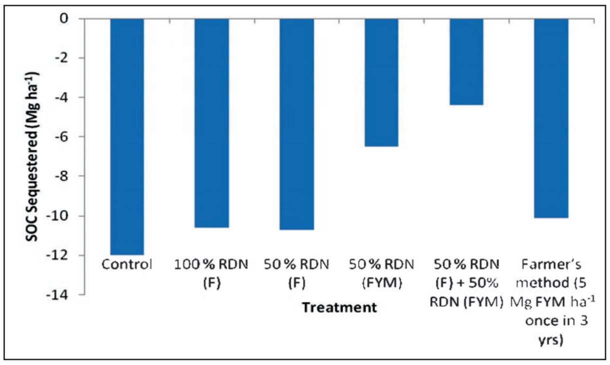

Fig. 5a. SOC sequestration in the profile affected by 18 years of pearlmillet-clusterbean-castor cropping and fertilization under semiarid conditions.

Soybean based system

The profile SOC stock differed significantly (P<0.05) among treatments (Table 6). The highest SOC stock of 69.9 Mg C ha^{-1} was observed in the 6 Mg FYM+ $N_{20}P_{13}$ ha^{-1} treatment followed by that of 68.7 Mg C ha^{-1} in the 5Mg CR+$N_{20}P_{13}$ ha^{-1} >that in the 6 Mg FYM ha^{-1} (66.9 Mg C ha^{-1})> 5 Mg CR ha^{-1} (63.6 Mg C ha^{-1})= 60 kg N+35 kg P (62.7 Mg C ha^{-1}), and the lowest (51.0 Mg C ha^{-1}) in the control (Srinivasarao *et al*., 2011f) (Fig. 6). Relatively higher percentage of SOC sequestration was observed in the 6 Mg FYM+$N_{20}P_{13}$ ha^{-1} treatment (37.1%) followed by those in the 5Mg CR+$N_{20}P_{13}$ ha^{-1} (34.7%) and 6 Mg FYM ha^{-1} (31.2%) treatments (Fig. 6a). The rate of SOC sequestration also followed a trend similar to that of the SOC sequestration. The data show that 41.7 and 22.0% of the biomass-C input was stabilized in FYM, and soybean/safflower CR, respectively.

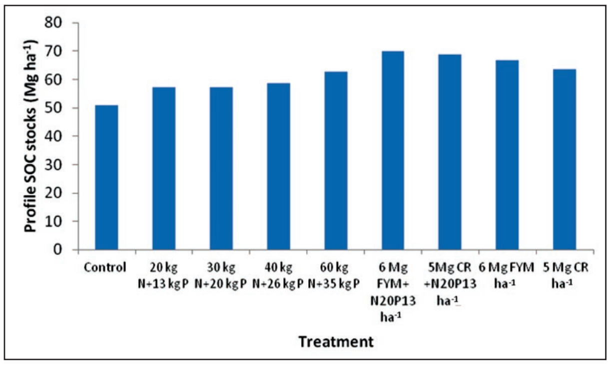

Fig. 6. The profile SOC stock for different fertilization treatments in 15 years of soybean-safflower cropping under semiarid conditions

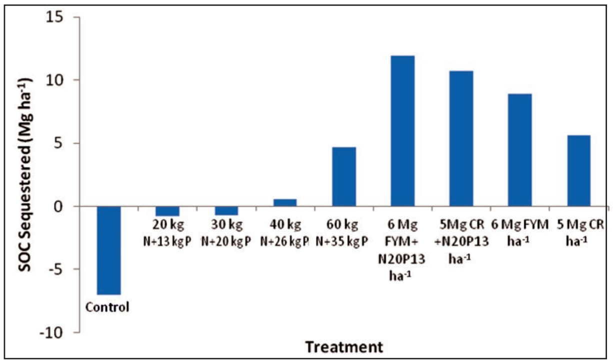

Fig. 6a. SOC sequestration of the profile for different fertilization treatments in 15 years of soybean-safflower cropping under semiarid conditions

Rice based system

The SOC stock (Mg C ha^{-1} to 1-m depth) in 2007 differed significantly (P<0.05) among treatments (Table 6), and was in the order 100% organic (FYM) (27.5) >50% organic (FYM)+50% RDF (24.0)>100% RDF (mineral) (20.5)>50% RDF+50% (foliar) (19.2)=50% RDF (mineral) (19.0)=farmer's practice (18.7) >control (17.8 Mg C ha^{-1}) (Srinivasarao *et al*., 2011g) (Fig. 7). In comparison with the control, % increase in SOC stock was in the order 100% organic (FYM) treatment (55.0) >50% organic (FYM)+50% RDF (35.2) >100% RDF (mineral) (15.3).This trend was reflected in the profile SOC stock of the respective treatments (Fig. 7a). The mean rate of change in SOC stock followed a trend similar to that of SOC stock (Table 6). The SOC stock declined in all but 2 treatments (100% FYM, 50% FYM + 50% RDF). The mean rate of SOC

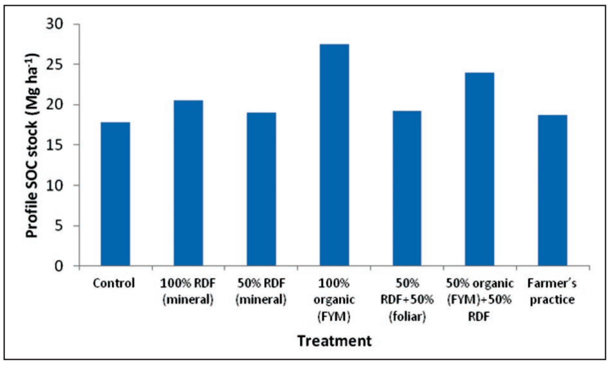

Fig. 7. Profile SOC stock as affected by 21 years of rice-lentil cropping and fertilization under sub humid tropical conditions

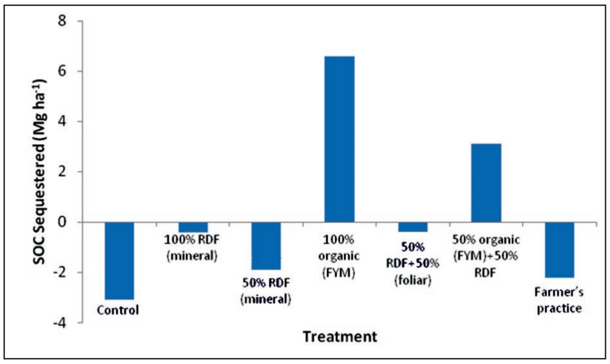

Fig. 7a. SOC sequestration in the soil profile as affected by 21 years of rice-lentil cropping and fertilization under sub humid tropical conditions

sequestration in two treatments which enhanced SOC stock over 21 years was 0.32 Mg ha^{-1} yr^{-1} for 100% FYM and 0.15 Mg ha^{-1} yr^{-1} for 50% FYM + 50% RDF. The results of the present study show that 13.4% C applied as FYM was stabilized in SOC stock.

Maintaining SOM above the critical level is necessary to sustain agronomic productivity and to minimize environmental degradation (Lal, 2010). However, maintaining or improving SOC stock in light-textured soils of arid and semi-arid regions is a major challenge (Lal, 2011). The prevailing low levels of SOC concentrations are attributed to soil-mining practices – little or no crop residue returned to the soil, excessive tillage, imbalance in fertilizer use and severe soil degradation. Loveland and Webb (2003) indicated that it is widely believed that threshold of about 2.0% organic carbon is appropriate for most regions. However, the extent to which organic matter in semi arid areas can be raised is not known nor are adequate levels for low rainfall areas agreed on.

Ploughing for seedbed preparation disturbs the soil, adversely affects the distribution and stability of aggregates, and exacerbates oxidation of SOM, and depletes the SOC stock (Kong *et al*., 2005). Although ploughing-induced depletion of SOC stock is widely observed (Wright and Hons, 2004; Lal, 2010), the magnitude of depletion depends upon the geographical location, crops/cropping systems, inherent soil properties, cropping history, and the duration of the fallow period (Davidson and Ackerman, 1993; Guo and Gifford, 2002; Mandal *et al*., 2008). Higher biomass and C input in 50 or 100% NPK through fertilizer combined with the use of FYM may be due to increased availability of deficient nutrients (i.e., N, K, Ca, Mg, S, Zn and B) with organic manure (Srinivasarao and Vittal, 2007).

Conclusions

Studies indicated that regular input of biomass-C along with chemical fertilizers is essential for improving soil quality in the semi arid tropics of India, and for minimizing the depletion of SOC stock under continuous cropping particularly in energy intensive double cropping regions. The use of chemical fertilizers at comparatively higher rate can also maintain the SOC level.

Future Line of Work

- There is an urgent need to launch long-term (>10 years) field experiments to quantify the influence of best management practices on the soil carbon sequestration in various ecosystems and crop production systems.
- Monitoring and verification of the rate of SOC sequestration in a transparent, cost-effective and credible manner is also an impediment to developing a user-friendly trading system.

- Quantification of the country's soil carbon sequestration potential in terms of various land use scenarios and management scenarios in spatial perspective by using soil carbon models.
- Information on the recommended land use and management practices for soil C sequestration, and what are the corresponding rates under ''on-farm'' conditions.
- What are the relevant processes of soil C sequestration (e.g., aggregation, humification, formation of secondary carbonates), and what is the residence time of C thus sequestered.
- Where land use/land use changes and soil management are a net sink for C, it is important to identify and implement policy instruments that facilitate realization of this sink.
- Some relevant research questions being asked to soil and tillage researchers in relation to C sequestration in agricultural soils so that a holistic package can be evolved for positive sequestration rates.

References

Biradar, C.M., Thenkabail, P.S., Noojipady, P., Li, Y., Venkateswarlu, D., Turral, H., Velpuri, M., Gumma, M.K., Gangalakunta, O.R.P., Cai, X.L., Schull, M.A., Alankara, R.D., Gunasinghe, S., Mohideen, S. 2009: A global map of rainfed cropland areas at the end of last millennium using remote sensing. International Journal of Applied Earth Observation & Geoinformatics 11, 114-129.

Blake, G.R., Hartge, K.H. 1986: Bulk density. P. 363-375. In A. Klute (ed.) Methods of soil analysis. Part 1. Physical and mineralogical methods. 2 nd ed. Agronomy Monograph. 9. ASA and SSSA, Madison, WI.

Davidson, E.A., Ackerman, I.L., 1993, 'Changes in soil carbon inventories following cultivation of previously untilled soils', Biogeochemistry 20, 161-193.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis, Global Change Biology 8, 345-360.

Jenkinson, D.S., Ayanaba, A. 1977. Decomposition of carbon-14 labeled plant material under tropical conditions. Soil Science Society of America Journal 41, 912–915.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C. 2005 The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. Soil Science Society of America Journal 69, 1078-1085.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., van Kessel, C., 2005. The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems, Soil Science Society of America Journal 69, 1078-1085.

Lal R. 2011. Sequestering carbon in soils of agro-ecosystems. Food Policy 36: S33-S39.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623-1627.

Lal, R. 2009. Soil carbon sequestration for climate change mitigation and food security. Souvenir, Platinum Jubilee Symposium on Soil Science in Meeting the Challenges to Food Security and Environmental Quality. Indian Society of Soil Science, New Delhi, pp 39-46.

Lal, R., 2010. Carbon sequestration potential of rainfed agriculture. Indian Journal of Dryland Agricultural Research and Development 25(1), 1-16.

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review, Soil Tillage Research 70, 1–18.

Majumder, B., Mandal, B., Bandyopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., Majumder, D. (2008): Organic amendments influence soil organic carbon pools and crop productivity in a 19 years old rice-wheat agroecosystems. Soil Science Society of America Journal 72, 775-785.

Mandal, B., Majumder, B., Adhya, T.K., Bandyopadhyay, P.K., Gangopadhyay, A. *et al.,* 2008, The potential of double-cropped rice ecology to conserve organic carbon under subtropical climate, Global Change Biology 14, 2139-2151.

Mandal, B., Majumder, B., Bandyopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaray, R.N., Mishra, A.K., Chaudhury, J., Saha, M.N., Kundu, S. 2007. The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. Global Change Biology 13, 1-13.

Nelson, D.W., Sommers, L.E. 1982. Total carbon, organic carbon, and organic matter. P. 101-129. In A.L. Page *et al*. (ed.) Methods of soil analysis. Part 2. 2 nd ed. Agronomy Monograph 9. ASA and SSSA, Madison, WI.

Paustian, K., Collins, H.P., Paul, E.A. 1997. Management controls in soil carbon. In: Soil Organic Matter in Temperate Ecosystems: Long-term Experiments in North America (eds Paul EA, Paustian K, Elliot ET, *et al*.), CRC Press, Boca Raton, FL. pp 15-49.

Schuman, G.E., Janzen, H.H., Herrick, J.E. 2002. Soil carbon dynamics and potential carbon sequestration by rangelands. Environ. Pollut. 116, 391-396.

Srinivasarao, Ch., Venkateswarlu, B., Rattan Lal, Singh, A.K., Vittal, K.P.R., Sumanta Kundu, Balaguravaiah, G., Vijaya Shankar Babu, M., Prasad, J.V.N.S., Ravindra Chary, G., Mandal, U.K. 2011a. Soil carbon sequestration and agronomic productivity of an Alfisol for groundnut-based system in an semiarid environment in southern India. Agronomy for Sustainable Development (In press).

Srinivasarao, Ch., Deshpande, A.N., Venkateswarlu, B., Rattan Lal, Singh, A.K., Vittal, K.P.R., Mishra, P.K., Sumanta Kundu, Prasad, J.V.N.S., Mandal, U.K. and Sharma, K.L. 2011d. Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi arid tropics of central India. Geoderma (In press).

Srinivasarao, Ch., Venkateswarlu, B., Rattan Lal, Singh, A.K., Sumanta Kundu, Vittal, K.P.R., Patel, J.J. and Patel, M.M. 2011e. Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearlmillet-clusterbean-castor rotation in western India. Land Degradation and Development (in press).

Srinivasarao, Ch., Venkateswarlu, B., Rattan Lal, Singh, A.K., Sumanta Kundu, Vittal, K.P.R., Sharma, S.K., Sharma, R.A., Jain, M.P. and Ravindra Chary, G. 2011f. Sustaining agronomic productivity and quality of a Vertisol under soybean-safflower cropping system in central India. The Journal of Science for Food and Agriculture (In press).

Srinivasarao, Ch., Venkateswarlu, B., Rattan Lal, Singh, A.K., Vittal, K.P.R., Sumanta Kundu, Gajanan, G.N., and Ramachandrappa, B. 2011c. Long-term effects of crop residues and fertility management on carbon sequestration and agronomic productivity of groundnut-finger millet rotation on an alfisol in southern India. International Journal of Agricultural Sustainability (In press).

Srinivasarao, Ch., Venkateswarlu, B., Rattan Lal, Singh, A.K., Vittal, K.P.R., Sumanta Kundu, Singh, S.R. and Singh, S.P. 2011g. Long-term Effects of Soil Fertility Management on Carbon Sequestration in a Rice-Lentil Cropping System of the Indo-Gangetic Plains. Soil Science Society of America Journal (In press).

Srinivasarao, Ch., Venkateswarlu, B., Singh, A.K., Vittal, K.P.R., Sumanta Kundu, Chary, G.R., Gajanan, G.N. and Ramachandrappa, B. 2011b. Critical carbon inputs to maintain soil organic carbon stocks under long term finger millet (Eleusine coracana (L.) Gaertn) cropping on Alfisols in semi arid tropical India. Journal of Plant Nutrition and Soil Science (In press).

Srinivasarao, Ch., Vittal, K.P.R., 2007, 'Emerging nutrient deficiencies in different soil types under rainfed production systems of India', Indian Journal of Fertilizers 3, 37-46.

Srinivasarao, Ch., Vittal, K.P.R., Venkateswarlu, B., Wani, S.P., Sahrawat, K.L., Marimuthu, S., Sumanta Kundu .2009. Carbon stocks in different soil types under diverse rainfed production systems in tropical India. Communication in Soil Science & Plant Analysis 40, 2338–2356.

Velayutham, M., Pal, D.K., Bhattacharyya, T. 2000. Organic carbon stocks in soils of India. In: Global Climatic Change and Tropical Ecosystems, Advances in Soil Science (eds Lal R, Kimble JM, Stewart BA), CRC Press, Boca Raton, FL. pp 71-95.

Wright, A.L., Hons, F.M. 2005. Tillage impacts on soil aggregation and carbon and nitrogen sequestration under wheat cropping sequences. Soil Tillage Research 84, 67-75.

Wright, A.L., Hons, F.M., 2004. 'Soil aggregation and carbon and nitrogen storage under soybean cropping sequences', Soil Science Society of America Journal 68, 507-513.