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Carbon sequestration potential of Indo-Gangetic agroecosystem soils

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Abstract: We estimate the distribution of carbon in soil profile in agroecosystems of Indo-Gangetic Plains and explore factors which control this distribution. The soil texture was loam in the upper soil layers but changed to silt loam as the depth increased. Bulk density increased with soil depth, and had a negative relationship with soil organic C. A significant positive correlation between SOC and clay content was observed. About 69 % of soil carbon in the profile was confined to the upper 40 cm soil layer where C stock ranged from 8.5 to 15.2 t C ha^{-1}. We estimate that the agricultural soils of Indo-Gangetic Plains may contain 12.4 to 22.6 t ha^{-1} of organic C in the top 1 m soil depth. Since agricultural soils contain significantly lower C content than the soils of natural forest ecosystem in the same climate zone, management practices such as residue placement and reduced or no tillage are required to enhance C sequestration. A mix of agroforestry with crop fields may be an ideal option to enhance C sequestration in soils.

Resumen: Estimamos la distribución de carbono en el perfil del suelo en agroecosistemas de las Planicies Indo-Gangéticas y exploramos los factores que controlan dicha distribución. La textura del suelo fue franca en las capas superiores del suelo, pero cambió a franco arcillosa conforme aumentó la profundidad. La densidad aparente aumentó con la profundidad y tuvo una relación negativa con el C orgánico del suelo. Se observó una correlación positiva significativa entre el C orgánico del suelo y el contenido de arcilla. Alrededor de 69 % del carbono del suelo en el perfil estuvo confinado a los 40 cm más superficiales de la capa de suelo, donde el almacén de C fluctuó entre 8.5 y 15.2 t C ha^{-1}. Estimamos que los suelos agrícolas de las Planicies Indo-Gangéticas pueden contener entre 12.4 y 22.6 t ha^{-1} de C orgánico en el metro superior del perfil del suelo. Dado que los suelos agrícolas poseen un contenido significativamente menor de C que lo suelos de ecosistemas forestales naturales en la misma zona climática, se requieren prácticas de manejo tales como la colocación de residuos y la reducción o la ausencia de labranza que promuevan el secuestro de C. Una mezcla de agroforestería con campos agrícolas puede ser una opción ideal para aumentar el secuestro de C en los suelos.

Resumo: Estimou-se a distribuição de carbono no perfil do solo em agro-ecossistemas nas planícies Indo-Gangéticas e explorar os factores que controlam esta distribuição. A textura do solo era argilosa nas camadas superiores do solo mas mudou para franco-argilosa à medida que aumentava a profundidade. A densidade bruta aumentou com a profundidade do solo, e apresentou uma relação negativa com o C orgânico. Observou-se um correlação positiva significativa entre o SOC e o teor de argila. Cerca de 69% do carbono do solo no perfil encontrava-se confinado à camada dos 40 cm superiores onde o stock de C oscilou entre os 8,5 e os 15,2 t C ha^{-1}. Estimou-se que os solos agrícolas das planícies Indo-Gangéticas poderão conter entre os 12,4 e os 22,6 t ha^{-1} de C orgânico na camada superior do 1 m superior da espessura do solo. Dado que na mesma zona climática os solos agrícolas contêm significativamente menor teor de C do que os solos dos ecossistemas florestais naturais, práticas de gestão tais como distribuição de resíduos ou lavoura reduzida ou mesmo não lavoura, são necessárias para intensificar o sequestro de C. Um misto de agrosilvicultura com campos de cultura pode ser

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uma opção ideal para sequestrar C nos solos.

Key words: Bulk density, carbon stock, soil organic carbon, soil profile, soil texture.

Soil organic carbon (SOC) has long been identified as a factor that is important to soil fertility as well as to the environment because of huge carbon sequestration potential of the soils. It has an important influence on the chemical and physical properties of the soil, and it can release nutrients through mineralization in forms available to plants (Lal 2004a). The amount of carbon (C) stored in soil organic matter (SOM) is one of the largest and most dynamic reservoirs of carbon in the global C cycle. It is about twice that stored in the biosphere and atmosphere combined (Schlesinger 1997). Soil C pool to 1 m depth is estimated at about 1550 Pg SOC and approx. 750 Pg inorganic soil C (Batjes 1996). This total soil C pool of 2,300 Pg is three times the atmospheric pool of 770 Pg and 3.8 times the vegetation pool of 610 Pg; a reduction in soil C pool by 1 Pg is equivalent to an atmospheric enrichment of CO_2 by 0.47 ppm (Lal 2001). Thus, any change in soil C pool would have a significant effect on the global C budget. Agricultural ecosystems are promising in this regard as they are among the most intensively managed of all ecosystems and often have been depleted in SOC. There is significant potential for soil C sequestration in croplands which is globally estimated to be about 0.9 ± 0.3 Pg C year^{-1} (Lal 2004b).

The present study was designed with an objective to estimate the distribution of carbon in soil profile in agroecosystems of Indo-Gangetic Plains which account for 13 % of the geographic area of India. The study also explores factors which may potentially enhance C sequestration in these soils.

Present study was performed at three different agro-ecosystems in two districts: Varanasi and Mirzapur of Uttar Pradesh situated between 25° 15′ N to 82° 56′ E and 25° 13′ N to 82° 04′ E, respectively. The altitude ranged between 76 and 82 m above mean sea level. In the Varanasi district two sites (i) Banaras Hindu University Agricultural Research Farm (Ag. Farm BHU) and (ii) Karasara village (farmer's field) lying about 10 km apart were selected; while in Mirzapur district Pirkhir village which is about 14 km from BHU, was selected. At all the sites crop pattern was rice-wheat-fallow.

Study sites experience a tropical moist sub-humid climate, characterized by strong seasonality with respect to temperature and precipitation. The year is divisible into a rainy season (July - September), a cool winter (November - February) and a hot summer (April - June). October and March constitute transitional months between seasons. The long term average rainfall is about 1100 mm. During the study period (2009) rainfall was 963 mm while temperatures ranged between 35 °C to 45 °C.

The soil is pale brown, silty loam, inceptisol with a neutral reaction. Soil is part of Indo-Gangetic Plains which is alluvial, well drained and moderately fertile being low in available nitrogen and potassium (Singh 1995). Soil samples were collected in January 2009 from 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm of the soil profile. Sampling was done in triplicate from each soil depth at each site. Soil analyses were done separately for samples of each soil depth.

Bulk density was determined by using soil corer (Piper 1944) and reported on dry weight basis. Soil moisture was analyzed by drying the known amount of soil at 105-110 °C for 24 h. For the analysis of total C and soil texture air dried soil samples were used. Soil texture was analyzed by pipette method (ISO 1998). Total organic C content of soil samples was determined by the dichromate oxidation method (Nelson & Sommers 1975).

Bulk density of the soil ranged from 0.93 to 1.07, 0.91 to 1.06 and 0.98 to 1.05 g cm^{-3} for BHU agricultural farm, Karasara agricultural farm and Pirkhir agricultural farm, respectively. Bulk density increased with soil depth up to 30 cm at BHU and Karasara, and up to 100 cm depth at Pirkhir. Overall there was a non-linear, positive relationship between bulk density and soil depth (Fig. 1a). Increase in soil bulk density with increasing soil depth is also reported by Affule *et al.* (2004) for tropical soils of Ghana. Low bulk density in upper

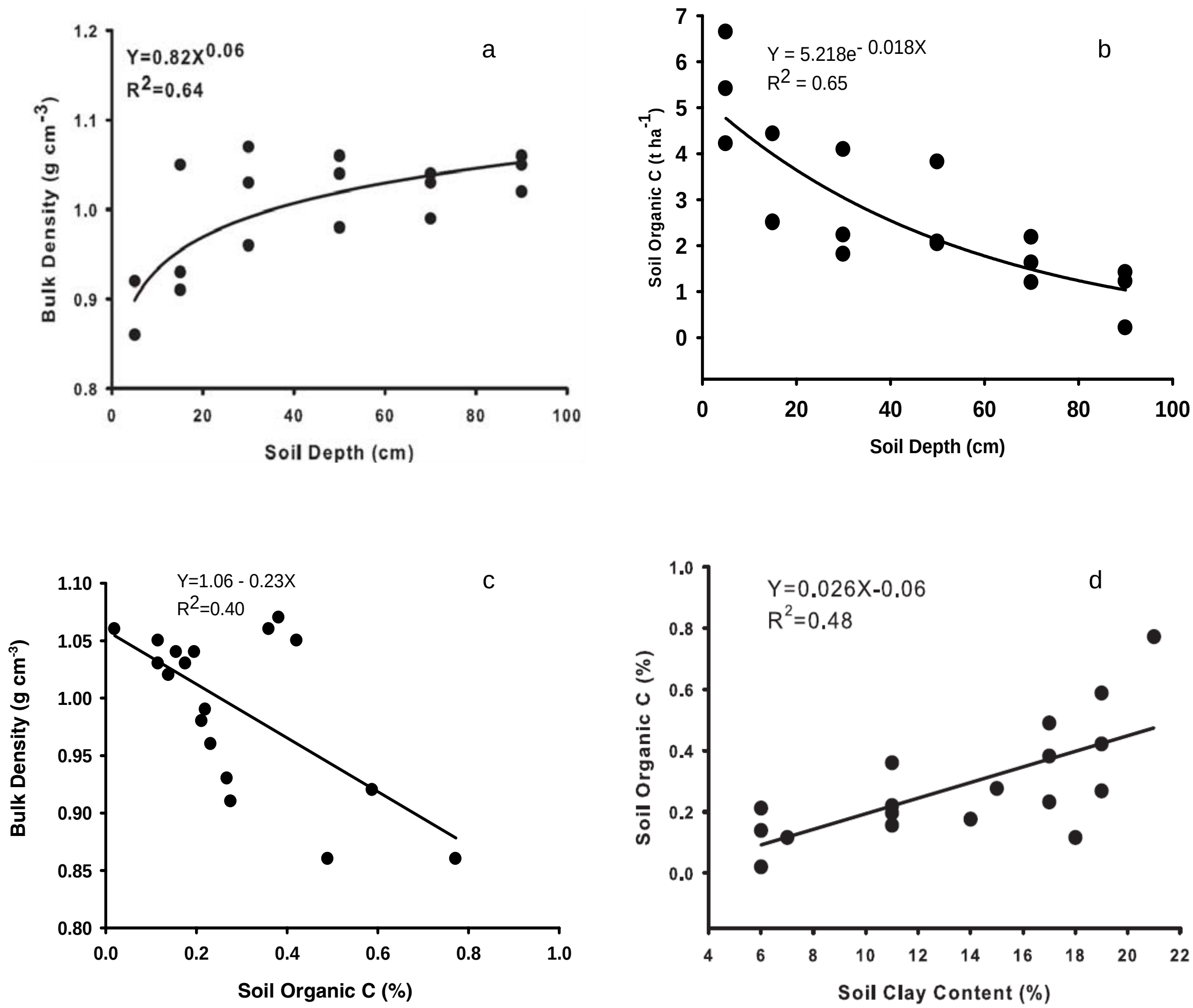

Fig. 1. Relationships among selected soil variables: (a) relationship between bulk density and soil depth; (b) relationship between soil organic C stock and soil depth; (c) relationship between bulk density and soil organic C; and (d) relationship between organic C content and clay content of soil.

soil horizons may result from high organic content, aggregation of soil materials, and sometimes low density vitric materials.

Sand, silt and clay contents varied across sites and soil depth (Fig. 2). Soil texture of all the three sites was loam in the upper layers but changed to silt loam as depth increased to 1 m. Thus sand was replaced with silt and clay as soil depth increased. Soil C stocks display a high spatial variability (coefficient of variation of 50 %, Cannell *et al.* 1999) but this variability is low in arable land. The mean soil C in 0-10 cm soil layer varied from 0.5 to 0.8 % with 23 % coefficient of variation (CV). Thus SOC decreased with depth (0-10 to 90-100 cm) from 0.8 to 0.13 for BHU agriculture farm, 0.5 to 0.02 for Karasara agriculture farm and 0.6 to 0.1 for Pirkhir agriculture farm. Across the sites, soil C stock had a non-linear negative relationship with soil depth (Fig. 1b). As a result, a negative relationship existed between bulk density and soil organic C content (Fig. 1c). A positive relationship occurred between soil C and clay content of upper 0-20 cm soil layer (Fig. 1d).

In soils, 30-60 % of the carbon is located in the clay-sized fraction (< 2 µm), presumably as clay-organic associations which are essential to the build-up and stability of soil structure (Emerson *et al.* 1986). Protection of SOC by silt and clay particles is well established (Ladd *et al.* 1985; Sorensen 1972; von Lützow *et al.* 2007). Jimenez *et al.* (2008)

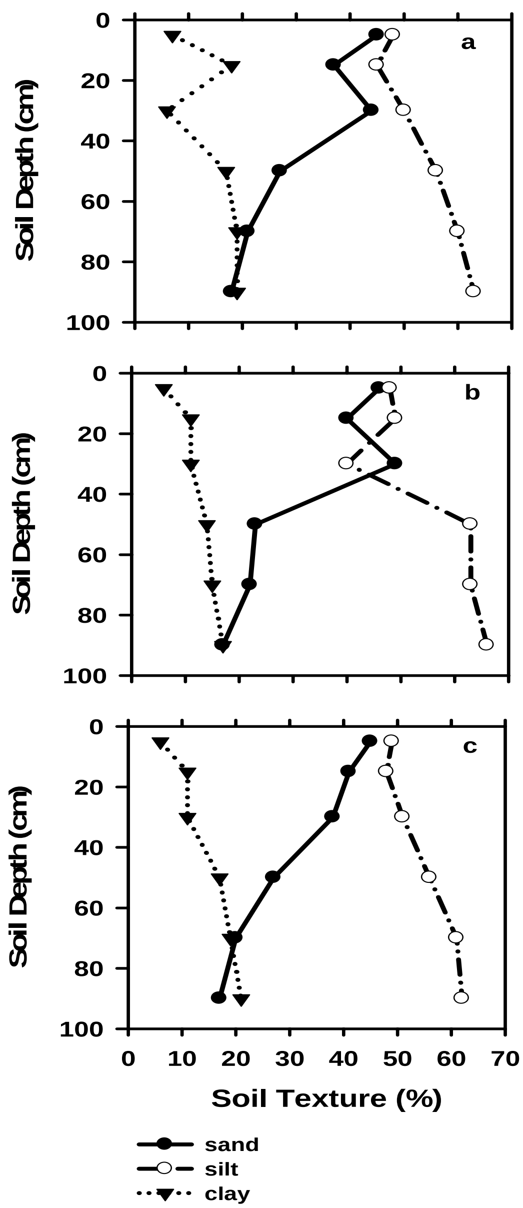

Fig. 2. Variation in soil texture in relation to soil depth (a) BHU Farm soil, (b) Karasara soil, (c) Pirkhir soil.

studied the soil C pool in different agroecosystems derived from the dry tropical forest of Guanacaste, Costa Rica and reported that the clay + silt fraction contains the highest C concentration.

In the global data set (Jobbágy & Jackson 2000), 33 to 36 % of the soil organic C in the top 1 m was found in the upper 20 cm and 56 to 59 % in the upper 40 cm. Potvin *et al.* (2004) reported that in the Sardinilla soils of Panama, between 60 and 77 % of the soil organic C to 1 m was found in the upper 20 cm, and 79 to 86 % in the upper 40 cm soil layer. In our study also, about 69 % of soil carbon in the profiles was confined to the upper 40 cm layer. It may reflect the distribution of roots in the agricultural land, roots are not deep enough to sequester SOC in deeper layers (Woods 1989). In our study, C stock up to 40 cm ranged from 8.5 to 15.2 t C ha^{-1} indicating that our values are also in the range reported for tropical soils (mean 17.2 t C ha^{-1}; Woomer *et al.* 2004).

Chhabra *et al.* (2003) reported the mean soil organic C density estimates based on 136 observations, from 70 t ha^{-1} in tropical dry deciduous forest to 162 t ha^{-1} in montane temperate forest for the top 1 m soil depth. Our estimates (12.4 to 22.6 t ha^{-1} for the top 1 m soil depth) for agricultural soils of Indo-Gangetic Plains are substantially lower than forest C stocks of India. Since most of the organic matter accumulated as crop produce is harvested and exported from the agro-ecosystems, these soils have low organic matter content compared to the natural ecosystems such as forests and grasslands found in the same climatic zone.

The large and relatively rapid changes in SOC with cultivation indicates that there is considerable potential to enhance the rate of carbon sequestration in soil with management activities that reverse the effects of cultivation on SOC pools (Post & Kwon 2006). It is impractical to suggest that the Indo-Gangetic agroecosystems should be converted back to forest or pasture for increasing C sequestration because they produce grain to feed about 40 % of the population of the country. There is a strong need to enhance our understanding of how terrestrial processes can be used to sequester atmospheric CO_2 in biochemically recalcitrant compounds in particular in deeper soil horizons (Lorenza *et al.* 2007). The turnover of light-fraction organic carbon (LF-OC) in the agroecosystems is linked to macroaggregate formation and its amount is substantially influenced by cropping and tillage (Beare *et al.*1994; Biederbeck *et al.* 1994; Bremer *et al.* 1994). Singh & Singh (1996) reported a positive relationship between organic C and macroaggregate percent in a variety of soils. SOC fractions derived from plant biomacromolecules (e.g., cutin and suberin, Winkler *et al.* 2005), from microbial processes (e.g., microbial lipids, Nierop *et al.* 2005), and from soil animals (e.g., chitin and proteins, Ekschmitt *et al.* 2005) commonly occur in soils. Bacteria produce melanins, waxes, terpenoids, and tetrapyrrole pigments that may be biochemically recalcitrant and resistant to biodegradation in soil (Gleixner *et al.* 2001). Such recalcitrant SOC fractions, which may constitute 15-50 % of the SOC pool, are the least dynamic organic C pools in terrestrial ecosystems. Soil management practices which increase the SOC pool may thus also increase the proportion of recalcitrant biomacromolecules (Lorenza *et al.* 2007). Data of Singh & Singh (1995) indicate that reduced tillage plots of BHU site have about 33 % more soil C (0-10 cm depth) compared to the conventionally tilled plots as reported in the present study. Therefore, the recalcitrant SOC pool can potentially be increased by increasing OM inputs into the ecosystem. Breeding and cultivating plant species rich in the aliphatic biopolymers is a potential option for increasing the proportion of recalcitrant biomacromolecules (Lorenza *et al.* 2007).

Long term experiments in Europe have shown that soils treated with organic amendments have between 20 % - 100 % more SOC than soils treated with inorganic fertilisers (Lal 2008). Best practice cropping, incorporating improved agronomic, nutrient, tillage and residue management are estimated to have an average annual greenhouse gas mitigation potential of 0.29 t C (or 1.07 t CO_2-eq.) ha^{-1} yr^{-1} in warm-dry climates and 0.63 t C (or 2.32 t CO_2-eq.) ha^{-1} yr^{-1} in warm-moist climates (Smith *et al.* 2008). Tropical soils of Indo-Gangetic Plains which account for 13 % of the geographical area of the country also have a huge potential for mitigating greenhouse gases through management practices such as reduced tillage and crop residue input practices.

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