Chapter 5

Soil organic carbon sequestration in rice based cropping system in Indo-Gangetic Plains

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The soil organic carbon (SOC) concentration of most soils in India is low because of the low clay contents in alluvial soils of the Indo-Gangetic plains (IGP), coarse-textured soils of southern India, and arid zone soils of north-western India (Dhir et al., 1991). These soils have been cultivated for centuries, and often with low off-farm input, based on systems that involve removal of crop residue and dung for fuel and other purposes. The prevalent low levels of SOC concentrations are also attributed to soil-mining practices of excessive tillage, imbalance in fertilizer use, little or no crop residue returned to the soil, and soil degradation (Lal, 2004). Hence in India, the importance of organic matter addition was considered so important that numerous studies with organic manures were conducted in seventies. The primary purpose was to determine their nutrient equivalence in comparison to chemical fertilizers. Despite the fact that organic manures contain almost all the essential plant nutrients and produce other non-nutrient benefits also, their value was principally assessed in terms of nitrogen (N) only (Katyal, 1993; Tandon, 1997). In long term experiments, the symptoms of 'fatigue', witnessed by stagnating or declining yields in intensive rice-based systems of IGP (Ram, 1998; Dawe et al., 2000; Duxbury et al., 2000; Ladha et al., 2003) is often attributed to decline in soil organic matter (SOM) quality and quantity (Dawe et al., 2000; Yadav et al., 2000; Ladha et al., 2003). Long term studies have shown that practices like improved fertilizer management, manuring and compost application, residue incorporation, crop rotation, green manuring, reduced tillage, adjusting irrigation method and restoration of waste land enhanced soil carbon build up and storage (Kimble et al., 2002). These practices not only promote sustainable agriculture but also mitigate the impact of climate change through both carbon sequestration and minimized emissions of greenhouse gases (GHGs). A single land use or management practice will not be effective at sequestering carbon (C) in all regions (Lal et al., 1998). The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal et al., 2007). In recent years, extensive attention has been paid to the sustainability and the effects of crop management practices on soil organic carbon dynamics and its sequestration in rice-wheat systems of IGP which is one of the largest production systems in the world.

Indo-Gangetic Plains

The name *Indo-Gangetic Plains* (IGP) is derived from the two river systems in the region *Indus* and *Ganges*. The IGP of India extends from 21°45′ to 31°0′ N latitude and from 74°15′ to 91°30′ E longitude and in India includes mostly the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal and the northern parts of Rajasthan and Tripura, covering a total area of 43.7 m ha, i.e. 13% of the total area of the country. The IGP in India is relatively homogenous in

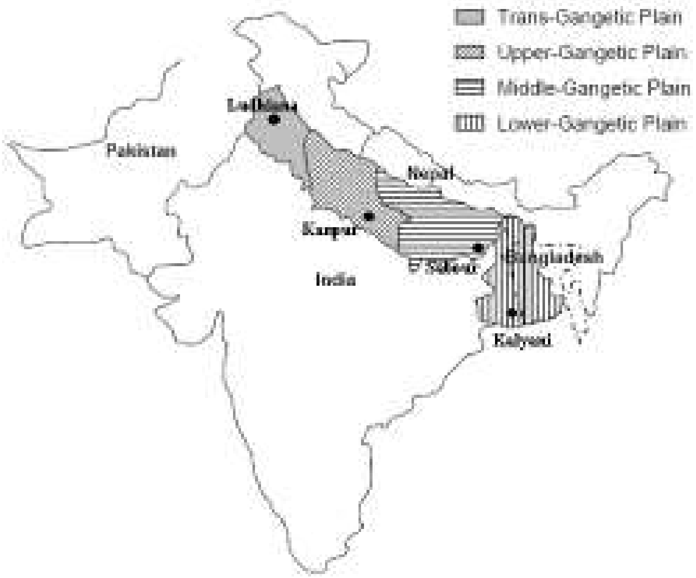

FIGURE 1. *Map of India (not to the scale) showing the Indo-Gangetic Plains*

vegetation but can be subdivided into four broad transects-the Trans (in the Indian Punjab and Haryana), Upper- (in the Western UP) Middle- (in the Eastern UP and Bihar), and Lower (in eastern India, West Bengal) Indo-Gangetic Plains (Fig. 1)

Climate in the IGP is dominated by the summer monsoon but varies strongly, going from west to east. The mean annual rainfall varies from 500-800 mm in the north-western part to as high as 1500-3200 mm in the east. Mean annual temperature in the IGP varies from 22 to 27°C. Summer temperatures are generally higher in the north-western part, reaching daytime temperatures as high as 45°C in June-July, whereas in winter temperatures may be as low as 4°C. In the eastern parts of the IGP, maximum temperatures in summer reach 38°C and minimum temperatures in winter may be as low as 10°C (White & Rodriguez-Aguilar, 2001).

Rice-wheat cropping system

Rice-wheat occupies about 7.15 m ha (66%) of the total area of 10.81 m ha of rice-based cropping in the IGP (Yadav & Subba Rao, 2001). The largest area of the rice-wheat rotation is found in Trans Gangetic Plains (TGP), followed by Middle Gangetic Plains (MGP) and Upper Gangetic Plains (UGP), while it occupies a small area in Lower Gangetic Plains (LGP) (0.23 Mha), mostly including other crops, such as summer rice, jute, gram and vegetables in the rice-wheat sequence. The rice–wheat (RW) system of IGP is of immense importance for the food security and livelihoods in India.

The two major cereals in the RW rotation have contrasting edaphic requirements. For rice, soil is puddled (wet tillage) and kept under continuous submergence. In contrast, wheat is grown in upland well-drained soil having good tilth. Puddling and transplanting are highly labor, water, time and energy intensive. The RW rotation creates alternate aerobic and anaerobic environment.

Salinity and sodicity affect a large area of IGP, in excess of 5.5 m ha; of which significant proportion of the land is utilized for agricultural production, including rice-wheat cropping. Compared to non-saline and non-sodic soil, SOC levels in these soils are lower, due primarily to reduced biomass production, hence reduced organic C input, but also to enhanced or similar organic C decomposition rates, the later is accentuated or maintained by increased dispersion of aggregates due to sodicity and hence exposure to protected organic C within aggregates, and its resolution and availability to the bacterial-dominated microbial population. Furthermore, as this source of SOC is depleted, even microbial biomass carbon (MBC) is utilized, which further reduces microbial biomass. Also, the dissolved organic C is subjected to leaching and run off losses (Wong et al., 2010)

Soil organic carbon dynamics under rice-wheat system

In IGP rice in wet season and wheat in dry season are cultivated in sequence, providing an alternate anaerobic and aerobic conditions round the year. Carbon mineralization was found to be three times slower under anaerobic than under aerobic conditions (DeBusk & Reddy, 1998). This slower decomposition rate, because of slower lignin degradation and the associated enrichment of young humus with phenolic compounds released from rice stubble decomposition, partially explains the relatively stronger accumulation of organic matter in wetland soils typical to rice soils in kharif. With an increasing number of annual irrigated rice crops, the phenolic nature of the humic acid fraction in soil increases (Olk et al., 1996). Microbial dynamics play a key role in C and N dynamics, as microbes are the active agents in soil organic natter (SOM) decomposition. Microbial biomass fluctuates under the influence of varying environmental conditions and substrate availability. Under aerobic conditions, aerobic microorganisms, especially fungi, dominate the soil microbial biomass and release phenols from decomposing lignin. Anaerobic microorganisms also decompose aromatic compounds such as phenols, but use different pathways (Evans, 1977). The phenolic structures liberated from parent lignin molecules often have a longer residence time in anaerobic soil than in aerobic soil and thus have more chance of polymerizing with some other component of SOM; consequently, SOM formed under submerged conditions undergoes stronger polymerization. Rice residues having higher C: N ratio decompose at slower rate than the wheat residues.

Soil organic carbon sequestration under rice-wheat system

An emerging concern in RW systems is the reduction in SOC-content and the associated reduced nutrient supplying capacity. Nambiar (1995) reported that SOC in treatments not receiving farmyard manure (FYM) declined in some long-term experiments (LTEs) in India, and that applications of FYM before either crop were effective in building up SOC and boosting crop yields. In the present rice-based cropping systems, crop residues are either burnt or removed from the field for stock feed and bedding, roofing and fencing. In India each year 19.6 million tonnes of straw of rice and wheat are burnt if used as recycled biomass, this potentially translates into 3.85 m t of organic carbon, 59,000 tonnes of nitrogen, and 2,000 tonnes of phosphorous and 34,000 tonnes of potassium and could be one of the potential options for improving the SOC stocks of soil. When residues are incorporated into the soil, mineral nitrogen is immobilized during decomposition, which may reduce nitrogen uptake and yield of the succeeding wheat crop by about 40% (Sidhu & Beri, 1989), whereas the combined use of rice or wheat straw and inorganic fertilizer in RW systems can increase the yield of rice and wheat (Mahapatra et al., 1991) and build up SOC.

Across the different agro-climatic zones of IGP, comparatively higher SOC content was observed in LGP followed by MGP, UGP and TGP, respectively. The higher SOC content in LGP and MGP over TGP and UGP is due to higher clay content in the soil, low land situation, reduced conditions due to incomplete drainage and humid climate (Nayak et al., 2012). Organic matter decomposition proceeds faster in sandy than in clayey soils (Katyal, 2001), while the rate of soil organic matter decomposition is lessened in lowland rice fields, apparently due to excessively reduced conditions (Watanabe, 1984). Because of the lack of oxygen under submerged conditions, even a modest oxygen demand for microbial activity can not be met if large pores are filled with water, resulting in a decreased rate of decomposition (Jenkinson, 1988). Therefore, there is an incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in soils (Sahrawat, 2004).

Continuous application of NPK for 23–26 year in RW system has resulted in significantly higher SOC over control in 0–15 cm soil depth across different agro-climatic zones of IGP. Intensive RW system in IGP without application of fertilizers (control) resulted in reduction (22 and

35% decrease) of SOC concentration over initial value in middle and lower IGP, respectively whereas at trans and upper IGP, it has more or less maintained the SOC level (Nayak et al., 2012). As initial SOC concentration was comparatively higher at middle and lower IGP than trans- and upper- IGP, it would be hard to maintain SOC contents without fertilization and/or organic matter addition in middle and lower IGP. However, because of very low initial value, the SOC concentration in the control plot was maintained at trans- and upper- IGP despite declining yield trend. Application of recommended dose of N–P–K resulted in increased SOC in surface soil over the initial level at all places except at LGP where a slight reduction was recorded. The higher stubble and root biomass retention commensurating with higher yield in the N–P–K fertilized plot might have improved the SOC in surface soil at all sites except at LGP where initial SOC value was comparatively higher than others. However, compared to unmanured/unfertilized control, the fields receiving recommended N–P–K fertilizer resulted higher SOC concentration in surface soil at all the places. Results of other long-term experiments have also shown that with optimum application of inorganic fertilizers, the SOC content has either been increased (Purakayastha et al., 2008a; Zhang et al., 2009) or maintained over the years (Biswas & Benbi, 1997). Substitution of 50% N through FYM or crop residue (CR) or green manure (GM) to rice has improved SOC significantly over NPK treated plots at all the locations. The addition of FYM, CR, and GM complemented with N–P–K increased the organic carbon content of soil over that achieved with N–P–K alone, due to additive effect of N–P–K and organics and interaction between them (Nayak et al., 2012). A similar build up of SOC due to cropping with the application of chemical fertilizer combined with manure (Rudrappa et al., 2006), paddy straw (Verma & Bhagat, 1992), and green manure (Yadav et al., 2000) were also reported from long-term experiments. Bharambe & Tomar (2004) reported an increase in organic carbon content in a RW system when inorganic fertilizers were applied along with FYM. Many long-term experiments have shown that both chemical fertilizer and manure application increased the SOC content in the soil, but the increases in SOC were much higher with organic manure (Christensen, 1996; Smith et al., 1997; Aoyama & Kumakura, 2001)

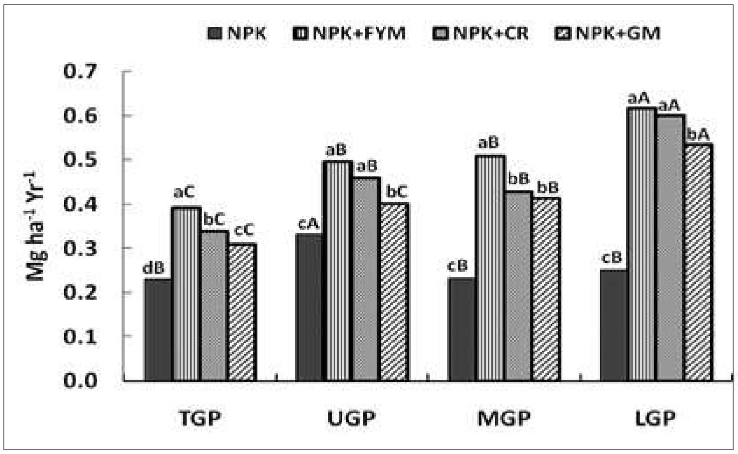

FIGURE 2. *Changes in soil organic carbon pool (Mg ha^{-1} Yr^{-1}) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letters are not significantly different in different treatments at same centre; means with the same uppercase letters are not significantly different in a treatment at different centres). Adapted from Nayak et al. (2012)*

Using the mass of SOC in the control treatment as reference point and number of years of interventions, Nayak et al. (2012) estimated the sequestration rate (rate of net SOC increase), which varied from 0.231 to 0.332 t ha^{-1}yr^{-1} in N–P–K treated plot under continuous RW cropping system in the different agro-climatic zones of IGP (Fig. 2). Among the treatments, NPK + FYM recorded significantly higher sequestration rate over all other treatments across all the agro-climatic zones except at LGP and UGP where the sequestration rate between NPK + FYM and NPK + CR were at par. Their study indicates that applications of N–P–K fertilizer with or without organics can sequester carbon in soils at all the sites of IGP. Response of SOC to carbon input has been controversial (Campbell et al., 2007; Purakayastha et al., 2008b). Hao et al. (2008) reported that combined applications of inorganic fertilizers (N–P and N–P–K fertilization) with or without manure can sequester carbon in soils at most of the sites of northern China. The soil carbon sequestration rates as reported by Nayak et al. (2012) vary from 0.08 to 0.98 t ha^{-1} yr^{-1} in IGP under the NPK, NPK + FYM, NPK + CR and NPK + GM treatments, which are comparable to those from other studies (Akselsson et al., 2005; Causarano et al., 2008; Kundu et al., 2007; Hien et al., 2006; Kroodsma & Field, 2006). The soil carbon sequestration with response to application of fertilizer complemented with organics was higher in LGP and MGP in humid climate than in TGP and UGP lying in semiarid climate. While budgeting C stocks in different eco-regions of Asia, Bronson et al. (1998) indicated a possible conservation or even increase in C stock in soil in the lowland tropics, despite high temperature prevalent throughout the years, which favours rapid mineralization of C. They opined that this was due to the relatively slow rate of soil C mineralization under anaerobiosis and also the large C inputs from nonvascular plants (photosynthetic algal communities) in the soil–flood water ecosystem. Soils rich in clay may have more potential to sequester carbon than those rich in sand and silt in the similar climate zone, due to the physical protection of mineral on SOC (Matus et al., 2008) which also partly explained the higher SOC sequestration rate at LGP having higher clay percent.

Soil organic carbon sequestration under salt affected soil

Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India, limiting the productivity of more than 2.5 m ha of otherwise arable lands in the IGP (Abrol & Bhumbla, 1971). Afforestation and reclaimation through agroforestry systems have been reported to increase soil organic matter content and improve the biological properties of sodic soils (Singh, 1996; Singh & Singh, 1997). Phytoremediation of sodic soil of IGP soil can sequester 0.826 Mg C ha^{-1} yr^{-1} under *Prosopis juliflora* plantations while intensive cropping of RW, including the application of gypsum amendments and optimum nutrient management, can sequester 0.689 Mg C ha^{-1} yr^{-1} (A.K. Nayak personal communication, 18 Feb, 2012). Kaur et al. (2002) suggested that various land –use system can sequester organic C in the range of 0.2 to 0.8 Mg C ha^{-1} per year. In long term experiment on a sodic soil, the changes in organic C under four tree species revealed that *Prosopis juliflora* is the most efficient species in terms of increasing SOC accumulation. However, the efficacy of application of amendments especially plant materials in enhancing SOC status and amelioration of these soils depends on the plant species and their ability to grow and produce biomass (Qadir et al., 2002). In general, it has been found that the amelioration of sodic and saline soils through the use of plants in the form of vegetation and crop residues is a slow process and this process can be enhanced by the application of amendments such as gypsum to reclaim the sodic soils followed by phytoremediation by cultivating RW. However, phytoremediation is advantageous that in addition to supplying organic matter, it provides source of plant nutrients, which are released during their mineralization in the soil. Moreover, plant roots produce root exudates and mucilages, resulting in increased microbial activity and microbial products in and around rhizosphere for aggregate formation and stabilization. Growing roots also provide channels for enhanced infiltration and hydraulic conductivity for rapid leaching of excess salts.

Remediation of even 10% area of salt- affected lands, achieving an estimated SOC sequestration of 0.2 Mg C ha^{-1} yr^{-1} over a 50-year period (approximately 50% of the potential C sequestration rate), may lead to 0.8 Pg C sequestered in SOC in these soils. Therefore, the potential for salt-affected soils to sequester SOC is large and significant. It is expected that large proportion of C sequestration will occur or result in the formation and stabilization of soil aggregates such as SOM-Ca^{2+}- clay aggregates, and as protected SOC against rapid microbial decomposition. However, research is required to validate this SOC sequestration mechanism after restoration of salt-affected soils, since, besides SOC benefits other benefits occur in improved physical and chemical characteristics of the soil.

Conclusions

There is a need for more quantitative assessment of the carbon sequestration potential of agricultural soils of IGP under different management practices for different soil types, climates and agricultural systems by supporting existing long term cropping system trial sites and by establishment of new ones where appropriate; quantifying interactions of SOC sequestration with emissions of GHGs and developing soil carbon models that can account for locally relevant agricultural management practices. There is also a need for assessment of how rehabilitation processes affect C cycling and C stocks, and how to maximise the accumulation of C stocks in the salt affected areas of IGP where SOC stocks are very small.

References

Abrol, I.P., & Bhumbla, D.R. (1971). Saline and alkaline soils in India, their occurrence and management. *World Soil Resources, FAO Report*, 41, 42-51.

Akselsson, C., Berg, B., Meentemeyer, V., & Westling, O. (2005). Carbon sequestration rates in organic layers of boreal and temperate forest soils - Sweden as a case study. *Global Ecology and Biogeography*, 14, 77-84.

Aoyama, M., & Kumakura, N. (2001). Quantitative and qualitative changes of organic matter in an ando soil induced by mineral fertilizer and cattle manure application for 20 years. *Soil Science and Plant Nutrition*, 47, 241-252.

Bharambe, A.P., & Tomar, A. (2004). Direct and residual effect of FYM and inorganic nutrients on rice–wheat cropping system in *vertisol*. *PKV Research Journal*, 28, 47-52.

Biswas, C.R., & Benbi, D.K. (1997). Sustainable yield trends of irrigated maize and wheat in a long-term experiment on loamy sand in semi-arid India. *Nutrient Cycling in Agroecosystems,* 46, 225-234.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., Noordwijk, M., & Van Garrity, D.P. (1998). Soil carbon dynamics in different cropping systems in principal eco-regions of Asia. In: R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (Eds.), *Management of carbon sequestration in soil*. (pp. 35-57). Boca Raton, NY: CRC Press.

Campbell, C.A., Vanden Bygaart, A.J., Grant, B.B., Zentner, R.P., McConkey, B.G., Lemke, R.L., Gregorich, E.G., & Fernandez, M.R. (2007). Quantifying carbon sequestration in a conventionally tilled crop rotation study in southwestern Saskatchewan. *Canadian Journal of Soil Science*, 87, 23-38.

Causarano, H.J., Doraiswarny, P.C., McCarty, G.W., Hatfield, J.L., Milak, S., & Stern, A.J. (2008). EPIC modeling of soil organic carbon sequestration in croplands of Lowa. *Journal of Environmental Quality*, 37, 1345-1353.

Christensen, B.T. (1996). The Askov long-term experiments on animal manure and mineral fertilizers. In D.S. Powlson, P. Smith, J.U. Smith (Eds.), *Evaluation of soil organic matter: Models using existing datasets*. (Vol. 138). (pp. 301-312). NATO, ASI: Springer, Heidelberg.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., & Zhen, Q.X. (2000). How widespread are yield declines in long-term rice experiments in Asia?. *Field Crops Research*, 66, 175-193.

DeBusk, W.F., & Reddy, K.R. (1998). Turnover of detrital organic carbon in a nutrient impacted Everglades marsh. *Soil Science Society of America Journal*, 62, 1460-1468.

Dhir, R.P., Chaudhary, M.R., Nath, J., & Somani, L.L. (1991). Constraints of sandy soils of arid and adjoining areas of western and northern India and their management. In T.D. Biswas (Ed.), *Soil-related constraints in crop production*. Indian Soc. Soil Sci. Bull. Vol. 15. (pp. 52-69). New Delhi, India.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., & Bronson, K.F. (2000). Analysis of long-term soil fertility experiments with rice–wheat rotations in South Asia. In *Long-term soil fertility experiments with rice–wheat rotations in South Asia.* Rice–Wheat Consortium Pap. Ser. No. 6. (pp. 7-22). New Delhi: Rice–Wheat Consortium for the Indo-Gangetic Plains.

Evans, W.C. (1977). Biochemistry of the bacterial catabolism of aromatic compounds in anaerobic environments. *Nature* (London), 270, 17-22.

Hao, X.H., Liu, S.L., Wu, J.S., Hu, R.G., Tong, C.L., & Su, Y.Y. (2008). Effect of long-term application of inorganic fertilizer and organic amendments on soil organic matter and microbial biomass in three subtropical paddy soils. *Nutrient Cycling in Agroecosystems,* 81, 17-24.

Hien, E., Ganry, F., & Oliver, R. (2006). Carbon sequestration in a savannah soil in southwestern Burkina as affected by cropping and cultural practices. *Arid Land Research and Management,* 20, 133-146.

Jenkinson, D.S. (1988). Soil organic matter and its dynamics. In A. Wild (Ed.), *Russell's soil conditions and plant growth* (11th ed.). (pp. 564-607). Longman Group UK Limited.

Katyal, J.C. (1993). Integrated nutrient management and supply: An overview. *Proceedings of Indian National Science Academy*, 59, 161-172.

Katyal, V.V. (2001). Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agronomy*, 46, 1-4.

Kaur, B., Gupta, S.R., & Singh, G. (2002). Bioamelioration of a sodic soil by silvopastoral systems in northwestern India. *Agroforestry Systems,* 54, 13-20.

Kimble, J.M., Lal, R., & Follett, R.R. (2002). Agricultural practices and policy options for carbon sequestration: What we know and where we need to go?. In J.M. Kimbel, R. Lal, R.F. Follett (Eds.), *Agricultural practices and policies for carbon sequestration in soil.* (pp. 512). New York: Lewis.

Kroodsma, D.A., & Field, C.B. (2006). Carbon sequestration in California agriculture, 1980-2000. *Ecological Applications,* 16, 1975-1985.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N., & Gupta, H.S. (2007). Carbon sequestration and relationship between carbon addition and storage under rainfed soybean wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research,* 92, 87-95.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., & Hobbs, P.R. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research,* 81, 159-180.

Lal, R. (2004). Soil carbon sequestration in India. *Climatic Change,* 65, 277-296.

Lal, R., Kimble, J.M., Follett, R.F., & Cole, C.V. (1998). *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*. Chelsea, Mich.: Ann Arbor Press.

Mahapatra, B.S., Sharma, G.L., & Singh, N. (1991). Integrated management of straw and urea nitrogen in lowland rice under a rice - wheat rotation. *Journal of Agricultural Science,* 116, 217-220.

Mandal, B., Majumder, B., Bandopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaroy, R.N., Misra, A.K., Chowdhuri, 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, 357-369.

Matus, F.J., Lusk, C.H., & Maire, C.R. (2008). Effects of soil texture, carbon input rates, and litter quality on free organic matter and nitrogen mineralization in Chilean rain forest and agricultural soils. *Communications in Soil Science and Plant Analysis,* 39, 187-201.

Nambiar, K.K.M. (1995). Major cropping systems in India. In V. Barnett, R. Payne, R. Steiner (Eds.), *Agricultural sustainability: Economic, environmental and statistical considerations*. (pp. 133-170). London: Wiley.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, Sonali. P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research,* 127, 129-139.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J., & Anderson, J.M. (1996). Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. *European Journal of Soil Science*, 47, 293-303.

Purakayastha, T.J., Rudrappa, L., Singh, D., Swarup, A., & Bhadraray, S. (2008a). Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize–wheat–cowpea cropping system. *Geoderma,* 144, 370-378.

Purakayastha, T.J., Huggins, D.R., & Smith, J.L. (2008b). Carbon sequestration in native prairie, perennial grass, no-tilled and cultivated Palouse silt loam. *Soil Science Society of America Journal*, 72, 534-540.

Qadir, M., Qureshi, R.H., & Ahmad, N. (2002). Amelioration of calcareous saline-sodic soils through phytoremediation and chemical strategies. *Soil Use and Management,* 18, 381-385.

Ram, N. (1998). Effect of continuous fertilizer use on soil fertility and productivity of a *Mollisol*. In A. Swarup, R.D. Damodarand, R.N. Prasad (Eds.), *Long-term soil fertility management through integrated nutrient supply*. (pp. 229-237). Bhopal, India: Indian Institute of Soil Science.

Rudrappa, L., Purakayastha, T.J., Singh, Dhyan., & Bhadraray, S. (2006). Long-term manuring and fertilization effects on soil organic carbon pools in a *typic haplustept* of semi-arid sub-tropical India. *Soil and Tillage Research*, 88, 180-192.

Sahrawat, K.L. (2004). Organic matter accumulation in submerged soils. *Advances in Agronomy*, 81, 169-201.

Sidhu, B.S. & Beri, V. (1989). Effect of crop residue management on the yields of different crops and on soil properties. *Biological Wastes,* 27, 15-27.

Singh, B. (1996). Influence of forest litter on reclamation of semiarid sodic soils. *Arid Soil Research and Rehabilitation,* 10, 201-211.

Singh, G. & Singh, N.T. (1997). Effect of land use practices on organic carbon dynamics of sodic soils. In R. Lal, J. Kimble, R. Follett (Eds.), *Soil properties and their management for carbon sequestration*. (pp. 89-105). USDA-Natural Resources Conservation Service, National Soil Survey Centre.

Smith, P., Powlson, S.D.S., Glendining, M.J., & Smith, J.U. (1997). Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology,* 3, 67-79.

Tandon, H.L.S. (1997). Organic residues: An assessment of potential supplies, their contribution to agricultural productivity and policy issues for Indian agriculture from 2000 to 2025. In I.S. Kanwar, S.C. Katyal (Eds.), *Plant nutrient needs, supply, efficiency and policy issues: 2000–2025*. New Delhi, India: National Academy of Agricultural Sciences.

Verma, T.S., & Bhagat, R.M. (1992). Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat–rice rotation in northern India. *Fertilizer Research,* 33, 97-106.

Watanabe, I. (1984). Anaerobic decomposition of organic matter. In *Organic matter and rice*. (pp. 2377-258). Manila, Philippines: International Rice Research Institute.

White, J.W., & Rodriguez-Aguilar, A. (2001). An agroclimatological characterization of the Indo-Gangetic Plains. *Journal of Crop Production,* 3, 53-65.

Wong, V.N.L., Greene, R.S.B., Dalal, R.C., & Murphy, B.W. (2010). Soil carbon dynamics in saline and sodic soils: A review. *Soil Use and Management,* 26, 2-11.

Yadav, R.L. & Subba Rao, A.V.M. (2001). *Atlas of cropping systems in India.* (pp. 96). Modipuram, Meerut, India: Project Directorate for Cropping Systems Research.

Yadav, R.L., Dwivedi, B.S., & Pandey, P.S. (2000). Rice–wheat cropping system assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Research,* 65, 15-30.

Zhang, W., Xu, M., Wang, B. & Wang, X.J. (2009). Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. *Nutrient Cycling in Agroecosystems,* 84, 59-69.

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