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Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030

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Abstract

The Global Environment Facility co-financed Soil Organic Carbon (GEFSOC) Project developed a comprehensive modelling system for predicting soil organic carbon (SOC) stocks and changes over time. This research is an effort to predict SOC stocks and changes for the Indian, Indo-Gangetic Plains (IGP), an area with a predominantly rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system, using the GEFSOC Modelling System and to compare output with stocks generated using mapping approaches based on soil survey data. The GEFSOC Modelling System predicts an estimated SOC stock for the IGP, India of 1.27, 1.32 and 1.27 Pg for 1990, 2000 and 2030, respectively, in the top 20 cm of soil. The SOC stock using a mapping approach based on soil survey data was 0.66 and 0.88 Pg for 1980 and 2000, respectively. The SOC stock estimated using the GEFSOC Modelling System is higher than the stock estimated using the mapping approach. This is due to the fact that while the GEFSOC System accounts for variation in crop input data (crop management), the soil mapping approach only considers regional variation in soil texture and wetness. The trend of overall change in the modelled SOC stock estimates shows that the IGP, India may have reached an equilibrium following 30–40 years of the Green Revolution. This can be seen in the SOC stock change rates. Various different estimation methods show SOC stocks of 0.57–1.44 Pg C for the study area. The trend of overall change in C stock assessed from the soil survey data indicates that the soils of the IGP, India may store a projected 1.1 Pg of C in 2030.

Keywords: GEFSOC Modelling System; SOC stock; Soil survey data; Indo-Gangetic Plains; India

1. Introduction

Knowledge of (SOC) is essential to sustain the quality and productivity of soils. Recently, the greenhouse effect has created great concern and the role of soils in mitigating this effect has been recognised. This has led to several studies on the quality, type, distribution and behaviour of SOC (Eswaran et al., 1993; Sombroek et al., 1993; Batjes, 1996). The first comprehensive study of SOC in Indian soils was conducted using data from different cultivated fields and forests with variable rainfall and temperature patterns (Jenny and Raychaudhuri, 1960). The study confirmed the effects of climate on C reserves in the soil. However, this study did not estimate the total C stock in Indian soils. Using ecosystem areas from different sources and representative global average C densities (Ajtay et al., 1979; Schlesinger, 1983) organic C in Indian soils was estimated as 23.4–27.1 Pg

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(Dadhwal and Nayak, 1993). Chhabra et al. (2003) estimated the organic C pool of Indian forest soils as 6.8 Pg C in top 1 m, using estimated SOC densities and Remote Sensing based area of forest types. Another attempt to estimate SOC stock was made by Gupta and Rao (1994) who reported an SOC stock in Indian soils of 24.3 Pg for soil depths ranging from surface to an average depth of 44–186 cm. The study used a database that included 48 soil series. However, the first comprehensive report of SOC stock in India, was carried out by Bhattacharyya et al. (2000) who estimated 9.5 Pg SOC at a depth of 0–0.3 m.

The Indian part of the IGP was selected for the present study due to the importance of these plains in terms of food production, food security and the pressure they are currently under to produce still higher yields for an increasing population. The Indian IGP, which covers approximately 13% of the geographical area of India, produces nearly 50% of the countries total food grains, which feed 40% of India's population. Traditionally the IGP has been a mainstay of rice and wheat production in India. However, recent reports on the land use and soils of the IGP indicate a general decline in soil fertility (Bhandari et al., 2002; Gupta, 2003). Soils that rarely showed any symptoms of nutrient deficiency in the past are now deficient in many nutritional elements. Long-term soil fertility studies have shown reductions in soil organic matter content as well as other essential nutrients. The biological activity of soils has also been shown to be gradually declining, resulting in reduced efficiency of applied inputs (Abrol and Gupta, 1998). Available literature and recent observational field visits to the IGP indicate that crop choices are changing very rapidly in the study area and that rice–wheat cropping systems are no longer the mainstay of the crop rotation (Durge et al., 2005). Few studies have been undertaken to assess SOC stocks in this changing scenario of crop diversification. Therefore, a need was identified to develop a system for estimating SOC stocks at the regional level for the IGP, India that is applicable over a range of soils and climates.

The GEFSOC Modelling System was developed in response to this need, using data from four contrasting eco-regions: the Brazilian Amazon, Jordan, Kenya and the Indo-Gangetic Plains, India. The system was developed during the Global Environment Facility Soil Organic Carbon (GEF-SOC) Project. The aim of the GEFSOC project was to produce a system that would enable end users to determine likely effects of proposed large scale land use and land management plans on SOC stocks at the national and sub-national scale and to provide the Intergovernmental Panel on Climate Change (IPCC) with information that would help them improve their guidelines on SOC stock estimation. Under this project, national and sub-national data sets of soils, climate, land use (historical and current) and land management were collated and formatted (Milne et al., 2007; Easter et al., 2007). All of these data sets are available in a comparable and standardised format. The GEFSOC project used existing datasets from a variety of sources with the idea of consolidating fragmented data into an easily accessible format. The present work is an effort to predict SOC stocks and changes for the IGP, India using the GEFSOC Modelling System and to compare output with stocks generated using mapping approaches based on soil survey data.

2. Materials and methods

2.1. Study site

The Indian IGP lies between 21°45′ to 31°0′N latitudes and 74°15′ to 91°30′E longitudes. These vast plains cover 43.7 Mha and include the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal, Himachal Pradesh, northern parts of Rajasthan and Tripura. The IGP includes 14 agro-eco-sub-regions (AESRs) out of a total of 60 AESRs reported in India (Velayutham et al., 1999) (Fig. 1).

The AESRs of the IGP have been detailed elsewhere (Bhattacharyya et al., 2004). In brief, on the basis of biotic species and climate (mean annual rainfall, MAR, mm; mean annual temperature, MAT, °C) the IGP can be grouped into seven bioclimatic systems. These systems can be organised in terms of increasing MAR and length of growing period (LGP) to allow higher cropping intensity without irrigation.

Information from 37 soil series (Arenosols, Cambisols, Fluvisols, Gleysols, Luvisols, Phaeozems, Regosols and Solonetz) was used to estimate soil C stock for the Indian IGP. These soils have been discussed in greater detail elsewhere (Bhattacharyya et al., 2004; Ray et al., 2004). The climatic datasets used for the C modelling exercise are average values from a 50-year period (Mandal et al., 1999) taken from 14 meteorological stations situated at different places throughout the IGP.

2.2. Current and future SOC stock estimates made using the GEFSOC Modelling System

The GEFSOC methodology to determine SOC stocks and changes is detailed in Easter et al. (2007). The system conducts analysis using three well-recognized models and methods: (1) the Century general ecosystem model; (2) the RothC soil C decomposition model and (3) the Intergovernmental Panel on Climate Change (IPCC) computational method. The system interacts with a SOTER soils database and databases of climate and land use built for the country or region the user intends to model. This paper presents the specific case for the IGP, India and focuses on results obtained with the dynamic Century model versus the empirical IPCC method.

The GEFSOC Modelling System involves a number of stages as outlined in Milne et al. (2007). As part of this process the user must (1) create land management tree diagrams which describe change in land use and land management over time for given areas of land and (2) build

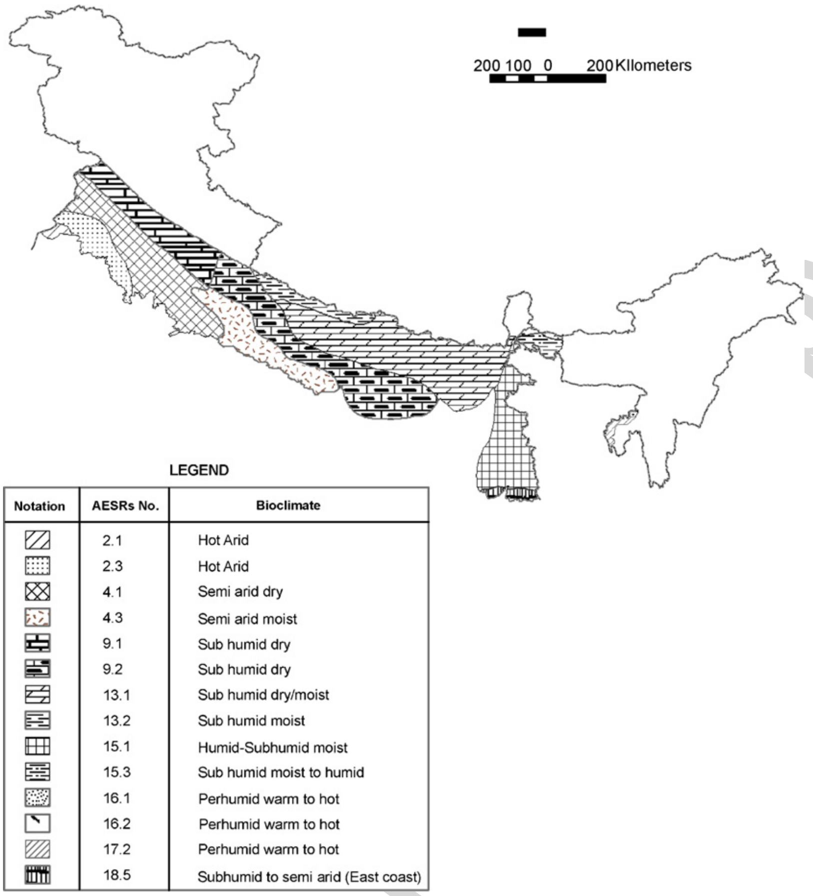

Fig. 1. Main agro-ecological sub-regions (AESRS) of the IGP, India.

different data layers (soils, climate and land use in a Geographical Information System) and build the various model files needed to run the models.

(1) Creating land management tree diagrams: details of how land management tree diagrams are built are given in Easter et al. (2007). In essence, for each land unit the user must enter management details of all crops, pasture species or trees that might be grown, determine crop rotations and then designate these to specific periods of time. Finally, the periods of time (starting from native vegetation) are put together to form chains or 'histories' of land management, with the proportion of the original area that changed land management being noted.

Historically the IGP has been considered as the most productive area of the Indian sub-continent. The cultivation of rice and other agricultural crops dates back before 8350 calculated years BP (Saxena et al., 2006). The available literature suggests that rice was the dominant crop even during the 16th Century in the eastern part of the IGP. In the northern and central part, wheat was grown in the 18th Century. Keeping in mind the similar land use histories across the region, it was decided to build land use histories for three representative AESRs in the northern, central and eastern part of the IGP and to use these histories for all AESRs. AESR 4.1 covers the state of Punjab, Haryana and Uttar Pradesh and occupies 30% of the IGP, India. AESR 9.2 covers part of eastern Uttar Pradesh and Bihar and occupies 14% of the IGP, India. AESR 15.1 covers West Bengal and part of eastern Bihar and occupies 15% of the IGP, India. For the entire Indian IGP, a total of 47 crops with 278 crop rotations were determined. The management sequence of AESRs 4.1, 9.2 and 15.1 is described in Table 1, as an example.

A representative management sequence chain for AESR 15.1 is shown in Fig. 2.

(2) Different data layers and model run files were built using regional scale data sets. A number of steps were employed;
- Crop information: to cope with the variety of crops grown in the study area, a crop data base was generated (Bhattacharyya et al., 2005). This was necessary as the existing models were originally produced using temperate data sets and do not, therefore, have default information on many of the crops and crop management practices for the IGP. Information on almost all of the cereals, pulses, oilseeds and vegetables grown in the Indian IGP was included.

Table 1
Crop histories and time periods used to model SOC Stock change in the IGP, India

AESR	Time period (year)	Sub-period (year)	Brief description	Major crops	Management
4.1	Base (1851–1900)	–	Annual grain production	Rice	No fertilizer, Rainfed
	Recent (1900–1975)				
		Recent 1 (1900–1940)	Monocrop, for sugarcane life saving irrigation	Corn, rice, wheat, cotton, sugarcane	Monocrop, rainfed
		Recent 2 (1941–1966)	Irrigation introduced, double-cropping began	Rice, wheat, corn, soybean	Irrigation
		Recent 3 (1967–1975)	Green revolution began	Rice, wheat	Fertilizer, irrigation
	Current (1976–2004)			Cotton, Berseem clover, soybeans	
		Current 1 (1976–1995)	Rice–wheat rotation dominates	Rice, wheat, cotton	Fertilizer, irrigation
		Current 2 (1996–2004)	Vegetables and oilseeds dominate	Rice, wheat, vegetables	Fertilizer, irrigation
	Future (2005–2030)	–	Three crops in a rotation dominate	Oilseed crops, rice, wheat, pulses, vegetables, oilseed crops	Three crops rotation
9.2	Base (1700–1825)	–	Annual grain production	Rice	No fertilizer, rainfed
	Recent (1826–1975)				
		Recent 1 (1826–1900)	Monocrop, in places Sorghum–wheat	Rice, wheat, cotton, sugarcane, sorghum	Monocrop, life saving irrigation for sugarcane only, no fertilizer
		Recent 2 (1901–1940)	No fertilization, rice dominant crop	Rice, wheat	Monocrop (occasionally double crops), no fertilizer
		Recent 3 (1941–1966)	Irrigation introduced, flood irrigation	Rice, wheat, cotton, sugarcane, sorghum	No fertilizer, flood irrigation
		Recent 4 (1967–1975)	Green revolution began	Rice, wheat, cotton, mustard	High yielding varieties, fertilizer, irrigation, plant protection measures
	Current (1976–2004)				
		Current 1 (1976–1995)	Rice and wheat are dominant crops	Rice, wheat, sugarcane, corn, berseem, soybean	Double crop fertilizer irrigation, plant protection measures
		Current 2 (1996–2004)	Three crops rotation began	Rice, wheat, corn, soybean, berseem	Three crops rotation, fertilizer, irrigation, plant protection measures
	Future (2005–2030)	–	Crop intensity increased	Rice, wheat, sugarcane, corn, soybean, berseem	Fertilizer, irrigation, plant protection measures
15.1	Base (1851–1966)	–	Annual grain production	Rice	No fertilizer, rainfed
	Recent (1967–1995)				
		Recent 1 (1967–1975)	Green revolution began	Rice, wheat	Double crop, fertilizer, irrigation, plant protection measures
		Recent 2 (1976–1995)	Triple-cropping in a few areas	Rice, wheat, vegetables, oilseeds	Fertilizer, irrigation, plant protection measures
	Current (1996–2004)	–	Cropping intensity increases	Rice, wheat, vegetables, pulses, oilseeds	Three crops rotation, fertilizer, irrigation, plant protection measures
	Future (2005–2030)	–	Every parcel of land is under agricultural use	Rice, wheat, oilseeds, pulses	Three crops rotation, fertilizer, irrigation, plant protection measures

N.B. Rice (*Oryza sativa*), corn (Zea mays), wheat (*Triticum aestivum*), cotton (*Gossypium* spp.), sugarcane (*Saccharum officinarum* L.), soybean (*Glycine max*), sorghum (*Sorghum vulgare*), Berseem clover (*Trifolium alexandrinum*), pulses (e.g. *Phaseolus radiatus* L., *Lens culinaris* Medik. and others), vegetables (e.g. *Brassica* spp., *Raphanus sativus* L., *Daucus carota* L. and others).

- Crop rotations: For all the AESRs in the IGP, a total of 1208 crop rotations were created. These crop rotations were the combination of various crop datasets made in the previous step (crop information). Examples of crop rotation for AESR 4.1 are shown in Table 2.
- Crop history: crop history datasets were utilized to prepare the land management tree diagrams. These datasets were collected from the published literature, farmers' knowledge, field experience and the history of the IGP, India (Bhattacharyya et al., 2005).

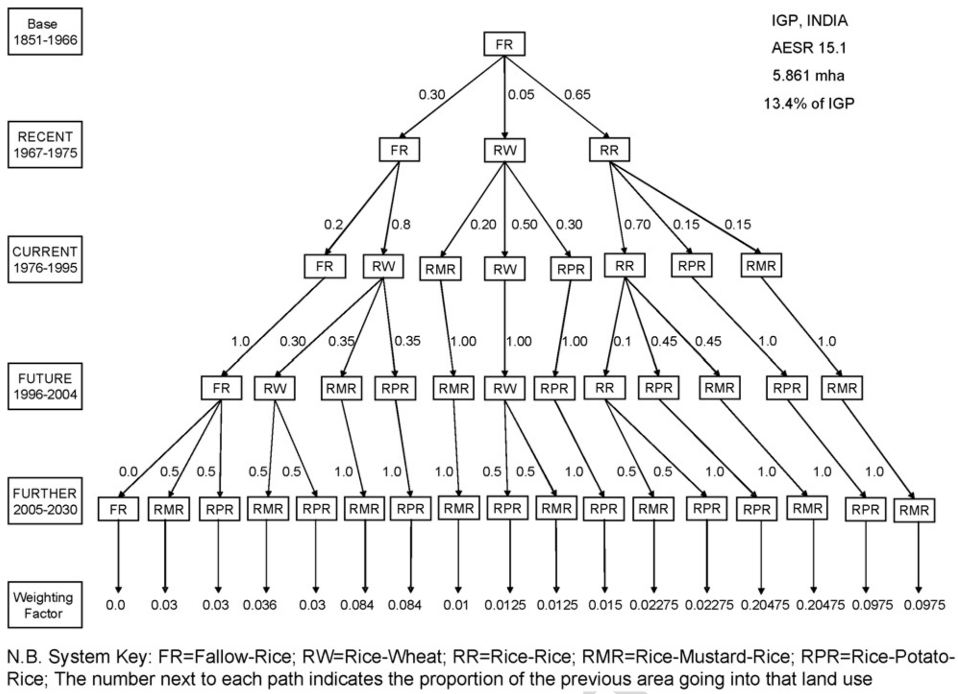

Fig. 2. Management sequence tree diagram for IGP, India (AESR 15.1).

Different periods were identified to capture various events in the AESRs. Table 1 shows the historical time periods for the selected AESRs in IGP, India.

- Climate layer: for the climate the complete datasets were collected and screened for all the AESRs.
- Soil layer: a soil map of India at 1:1 M scale was prepared during the national soil survey programme by categoric and cartographic generalization of all 1:250,000 scale maps (Staff NBSS&LUP, 2002). These materials have been used by the GEFSOC project to develop soil and terrain (SOTER) datasets for IGP, India (Chandran et al., 2005; Batjes et al., 2004). The study area has been characterized using 36 unique map units corresponding to 497 polygons, which cover all the agro-ecological regions. The IGP, India was surveyed during the 1980's to establish benchmark soils and these have been used to characterize the dominant soil of each map unit.

Table 2
Examples of crop rotations in AESR 4.1

Serial number	Acronym	Crops
1	RBm	Rice–berseem
2	RBmW	Rice–berseem–wheat
3	RCbBr	Rice–cabbage–brinjal
4	RCfT	Rice–cauliflower–tomato
5	RCrOk	Rice–carrot–okra
6	RCtT	Rice–cotton–tomato
7	RGT	Rice–garlic–tomato
8	RM	Rice–mustard
9	ROOK	Rice–onion–okra
10	RRdBr	Rice–raddish–brinjal
11	RW	Rice–wheat
12	RWMg	Rice–wheat–moong
13	SW	Sorghum–wheat

N.B. Rice (*Oryza sativa*), wheat (*Triticum aestivum*), cotton (*Gossypium* spp.), sorghum (*Sorghum vulgare*), Berseem clover (*Trifolium alexandrinum*), carrot (*Daucus carota* L.), Mustard (*Brassica juncea*), Cabbage (*Brassica olercea* L. var. *capitata* L.), cauliflower (*Brassica olercea* L. var. *botrytis*), tomato (*Lycopersicon esculentum* Mill), bringal (*Solanum melongena*), okra (*Abelmoschus esculentus*), garlic (*Allium sativum* L.), onion (*Allium cepa* L.), raddish (*Raphanus sativas* L.) and moong (*Phaseolus radiatus* L.).

2.3. SOC stock estimates using a mapping based approach

SOC content of the benchmark soils was determined following Walkley and Black's method (Jackson, 1973). The size of total C stock is calculated following the method described by Batjes (1996). The first step involves calculation of SOC by multiplying the proportion of organic C in a given horizon (g C g^{-1}) by bulk density (Mg m^{-3}) and the thickness of the horizon (m) for individual soil profiles with different thickness varying from 0–0.3, 0–0.5, 0–1.0 to 0–1.5 m. In the second step, the total SOC content (in Mg m^{-2}) determined by this process is multiplied by the area (Mha) of the soil unit distributed in different agro-ecological sub-regions (AESR) (Velayutham et al., 1999). The total SOC content is given in Pg. The total SOC stock was calculated using Eq. (1).

$$\text{C stock in soil Pg} = \frac{\text{C content} \times \text{BD} \times \text{area} \times \text{depth}}{10} \quad (1)$$

where C content is given in g C g^{-1}, BD in Mg m^{-3}, area in Mha, depth in m and C stock in Pg.

Table 3
Carbon stocks in the soils of the IGP, India

Region	Soil depth range (cm)		
	0–30 Pg	0–100 Pg	0–150 Pg
IGP, India[a]	0.63 (6.45/0.30/0.09)[b]	1.56 (6.23/0.39/0.10)[b]	2.00 (6.67/0.32/0.08)[b]
India[c]	9.77	25.04	29.97
Tropical regions[d]	201–213	384–403	616–640
World[d]	684–724	1462–1548	2376–2456[e]

[a] Bhattacharyya et al. (2004).
[b] Values in parentheses indicate % of stock in India, Tropical regions and the world, respectively.
[c] Bhattacharyya et al. (2000).
[d] Batjes (1996).
[e] Estimates are for 0–200 cm.

Table 4
Soil organic carbon stock estimates for the IGP, India

Study	System	Method	Year of stocks	SOC stock (Pg)
Bhattacharyya et al. (2004)	Benchmark soil series	Laboratory and cartography	1980	0.66[a]
GEFSOC (field work)	Benchmark soil series	Laboratory and cartography	2005	0.88[a]
Batjes et al. (2006)	Benchmark soil series	Extrapolation from secondary data based on Chandran et al. (2005)	1990	0.572–0.587[b]
GEFSOC	IPCC	Soil, climate and land use classification method	2000	0.97[b]
GEFSOC	Century model	Model simulation	2000	1.44[a]

[a] For the first 20 cm soil depth.
[b] For the first 30 cm soil depth.

3. Results

3.1. Regional SOC stocks using soil survey data

SOC stocks of the IGP were estimated using the benchmark soil datasets collected during the 1980's amounting to 0.63 and 2.00 Pg in the first 30 and 150 cm depth of soils, respectively (Table 3). This corresponds to some 6% of the total SOC stock of India (Bhattacharyya et al., 2004). SOC stocks of the Indian IGP correspond to less than 0.4% of the total for tropical regions (Table 3). According to Velayutham et al. (2000), about 70% of India falls in the SOC-deficient zone based on the low content of organic C in the topsoil (<1%; 0–30 cm).

The same 37 benchmark spots were revisited to collect land use data and soil samples during 2004–2005. The new soil samples were used to calculate the SOC stock for the year 2005 which are estimated at 0.88 Pg C in the first 20 cm. Comparison of the SOC stocks for 2005 and 1980 for each benchmark soil series vis-à-vis the dominant crop rotation would suggest that the SOC stock has appreciably increased in the rice–wheat crop rotation areas. In addition, based on this limited data set it appears that the total SOC stock has increased from 0.66 to 0.88 Pg in the first 20 cm depth of soils (Table 4).

3.2. Regional SOC stocks and stock changes using the GEFSOC Modelling System

3.2.1. Land use change scenario in the Indian IGP for the GEFSOC SOC estimates

Historical, current and projected land area under different cropping systems in the Indian IGP are shown in Fig. 3. This scenario involves a marked increase in crop intensification from double-cropping systems that include rice to rice–wheat and triple-cropping systems that include rice. Double-cropping refers to crop rotations with two crops grown in a year and triple-cropping refers to crop rotations with three crops grown in a year. There is a general trend in the Indian IGP toward crop diversification and triple-cropping systems, with the introduction of vegetables, oilseed, fibre and forage crops into rotations with rice and wheat remaining as the dominant crops. The small areas of land in fallow-rice and pasture-forest systems are predicted to be converted into other cropping systems by 2030. In addition, land under other crops (largely rotations of cotton with other crops) is expected to remain approximately the same throughout the modelling period.

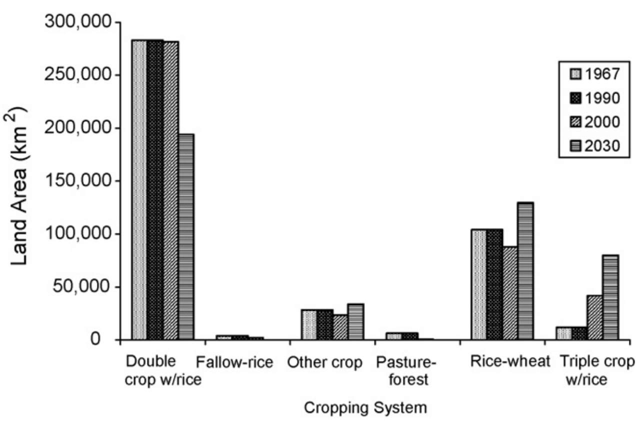

Fig. 3. Historical (1967), current (1990, 2000) and predicted (2030) area in the Indian IGP under different cropping systems.

3.2.2. Modelled SOC stocks in paddy and non-paddy soils

The IGP, India has been traditionally considered as a rice growing area. To determine the SOC stock in rice and non-rice growing areas, the GEFSOC output data sets were analysed using the soil information from SOTER in terms of drainage. By and large poorly and imperfectly drained soils are found in the low lying areas of the IGP where paddy is commonly grown (Sahrawat, 2006). These areas are characterized by soils showing mottles and other redoximorphic features confirming aquic moisture regimes (Soil Survey Staff, 2003). According to the Century model the lowland paddy soils have a stock of 0.66 Pg organic C as compared to 0.62 Pg in the non-paddy soils for the year 1980. According to our field data lowland paddy soils contain 51–52% of the total SOC stock of the IGP, India. It appears that the stock in the non-paddy soils has remained stable ~48–49% during the last 40 years. The SOC stock change rate, on the other hand, decreased during the period between 1990 and 2015. After that, the projected stock seems to be reaching a quasi-equilibrium (QE) value of 0.140–0.009 Tg C year^{-1} in the lowland paddy soils. The overall change rate of SOC stock is 0.150, 0.017 and 0.012 Tg C year^{-1} in 1990, 2000 and 2030, respectively.

3.2.3. IPCC output

Soil C estimated using the empirical IPCC method show little change over the period 1967–2030 (Fig. 4). As the method relies on classification of land area into distinct management and land use categories to determine C stocks, changes in SOC are driven by changes in the area distribution of land use systems over time. Further, default values for SOC per land use category are used in this Tier 1 approach. There is relatively little land use change in the IGP over the modelling period, as most of the land has been under intensive agricultural uses. Hence, using global default parameters as the basis for classifying management systems under the IPCC method, most land remains under the same or very similar classification throughout the period considered.

3.2.4. Century output

According to the Century model, there will be a 21% decrease in SOC stocks in the IGP from 1967 to 2030, with a

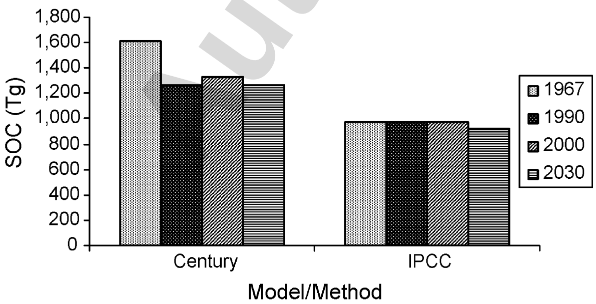

Fig. 4. Modelled SOC stocks according to CENTURY and the empirical IPCC method of the GEFSOC system.

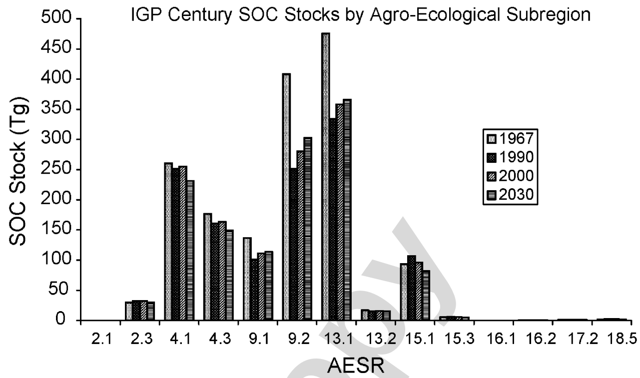

Fig. 5. SOC stock for 1967, 1990, 2000 and 2030 according to the Century module of the GEFSOC Modelling System by agro-ecological sub-regions in the Indian IGP.

dynamic equilibrium having been reached by about 1990 and relatively little change until 2030 (Fig. 4). SOC stocks by AESRs simulated by the Century model are shown in Fig. 5. Three of the AESRs (4.1, 9.2 and 13.1) dominate the SOC stocks in the region being responsible for 69% of the total. Of the remaining AESRs, six of them (AESR 2.1, 13.2, 15.1, 16.1, 16.2, 17.2 and 18.5) have negligible SOC stocks compared with the others, representing less than 1% of the total. Similar observations were made earlier using soil survey data for the IGP (Bhattacharyya et al., 2004). The SOC stocks for the three dominant classes of cropping systems are shown in Fig. 6. They include rice–wheat, double-cropping (other than wheat) with rice and triple-cropping with rice.

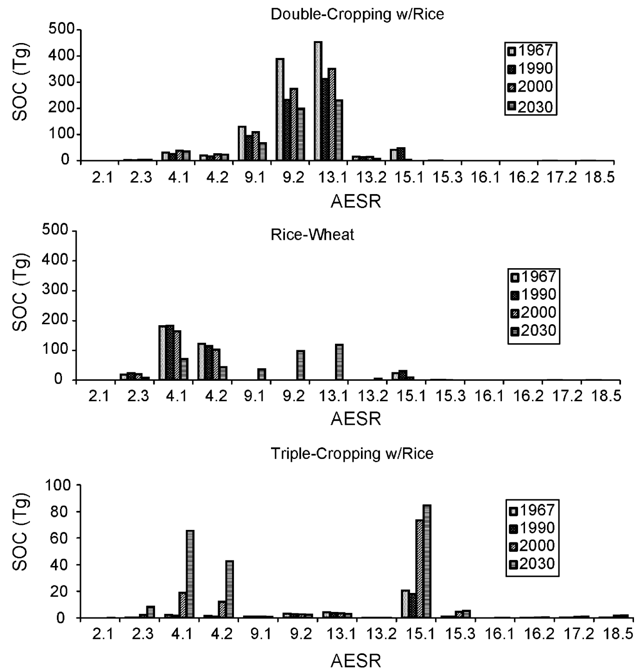

Fig. 6. GEFSOC modelled trends (CENTURY) in SOC by agro-ecological sub-region for the dominant cropping systems in the Indian IGP (W/Rice, with rice).

The GEFSOC Century model simulations suggest that SOC in the double-cropping systems that include rice in AESRs 9.1, 9.2 and 13.1, will drop due to the farmers' decision to shift to other cropping systems and losses of soil C resulting from intensification of cropping. SOC stocks in rice–wheat systems in these AESRs will increase substantially. AESRs 2.3, 4.1 and 4.2 will see substantial decreases in SOC stocks from rice–wheat systems as lands are taken out of rice–wheat and put into triple-cropping systems that include rice.

3.3. Comparison of survey based versus modelled SOC stocks

The SOC stock estimated using the benchmark soil and survey data is lower than the modelled SOC stock obtained using the GEFSOC Modelling System. Analysis of The GEFSOC Modelling System output show that the overall change in SOC stock is +0.2 Tg C year^{-1}, which indicates that perhaps the IGP may have reached quasi-equilibrium in terms of SOC after 30–40 years of the Green Revolution (Naitam and Bhattacharyya, 2004). It has been reported that soil systems attain quasi-equilibrium after accumulation of organic matter as well as loss of SOC over time (Naitam and Bhattacharyya, 2004). The time to attain the QE values of organic matter depends on the land-use system, among other factors. Thus, SOC levels often show tooth-like cycles of accumulation and of loss (Johnson, 1995). After each change in land-use system, a period of constant management is required to reach a new QE stage. It has been reported that under natural vegetation, SOC tends to attain QE within 500–1000 years in a forest system (Jenny, 1950; Dickson and Crocker, 1953), 30–50 years in an agricultural systems after forest clearing (Arrouays et al., 1995; Johnson, 1995; Batjes and Sombroek, 1997), 5–15 years in an agricultural systems after forest clearing in red soils (Luvisols) in Orissa, India (Saikh et al., 1998) and 20–50 years in the black soils (Vertisols) of central India (Naitam and Bhattacharyya, 2004). The QE of 30–40 years obtained with the GEFSOC Modelling System is within the range given by other studies.

Two previous studies estimated SOC inventories in the IGP. Bhattacharyya et al. (2004) extrapolated soil C measurements from 48 benchmark sites measured in 2004 to represent soil series throughout the IGP. Batjes et al. (2007) used published soil data for the IGP collated in SOTER format (Chandran et al., 2005) to estimate soil C stocks for 1990 (Table 4). The various methods indicate SOC stocks in a broad range of 0.57–1.44 Pg C.

Several options could be used to refine the existing SOC stock estimations for the region. Increasing the sample size and map unit detail to represent the diverse soil and agricultural regions would allow more detailed model runs using the GEFSOC System. Refinement of the land use, and land management factors in the empirical IPCC method, using specific research results from the IGP, may improve GEFSOC and IPCC estimates. Further, consideration of other soil properties, besides clay content and wetness, and processes in the GEFSOC Modelling System would be useful, for example land use and management induced changes in soil salinity, sodicity and carbonate content (Bhattacharyya et al., 2004; Pal et al., 2003).

3.4. Change rate of SOC-effect of crop rotation

The influence of various management practices in terms of crop type and crop combinations on SOC stocks was analysed from the model datasets. The change rate of SOC stock in various crop rotations was analysed in different AESRs. Table 5 gives the average SOC stock change rate by crop rotation. AESR 15.1 representing the humid part of the IGP shows an SOC change rate for rice–mustard (*Brassica juncea*)–rice and rice–potato (*Solanum tuberosum*)–rice as negative from 1990 to 2030. An introduction of three crops into a rotation without adequate nutrient management, may be exhausting the soil.

A modelled rice–wheat (R–W) system shows an overall decline in SOC stock. However, in AESR 4.1, the R–W system shows a positive SOC stock change rate from 1990 to 2030, largely due to intensive agriculture involving irrigation and addition of extra N-fertilizers. In AESR 9.2, the large gain in SOC stock in 1990 might be due to these reasons. Unlike the northern and eastern part of IGP, in this zone, represented by AESR 9.2 (comprising of Bihar and the eastern part of Uttar Pradesh states), subsistence agriculture persists. This involves poor seeds, low rate of fertilizers and sometimes addition of organic manures. This has caused low yield of crops and relatively low SOC removal from the soils causing a greater SOC stock. However, over a decade (1990–2000), these trends disappear and ultimately by 2030 a negative change is predicted to occur. In AESR 15.1 the degree of negative change decreases during 1990–2000. According to our scenarios, the R–W cropping system is assumed to have been discontinued between 2005 and 2030 and so no values were available for comparison (Fig. 7).

SOC depletion continues when potato and mustard are introduced in the rice–rice system in AESR 15.1. Interestingly, the SOC stock changes positively when Berseem (*Trifolium alexandrinum*) is introduced as a fodder crop in the rice–wheat crop rotation in AESRs 4.1 and 9.2, indicating more C accumulation caused by the introduction of a leguminous crop. Soil survey data indicates an overall change rate of +8.8 Tg year^{-1} and suggests that if this trend continues then the IGP, India might store SOC to the tune of 1.1 Pg by 2030 in the first 30 cm depth of soils.

4. Discussion

The consideration of SOC change rates is perhaps more important than the actual stock values that the GEFSOC modelling system provides for the Indian IGP. Land

Table 5
Average SOC stock change rate in different AESRs of IGP, India determined using output of the GEFSOC Modelling System

Crop rotations	SOC change rate Tg year^{-1}			Remark
	1990	2000	2030	
AESR 15.1				
Fallow-rice	−0.031	−0.156	–	Land area will not remain fallow during 2030
Rice–mustard–rice	0.049	−0.328	−0.136	Still changing
Rice–potato–rice	0.139	−0.169	−0.052	Still changing
Rice–rice	−0.016	−0.008	–	Crop rotation is changing
Rice–wheat	−0.463	−0.142	–	New crops are introduced
AESR 4.1				
Cotton–berseem	0.337	0.012	0.000	Quasi-equilibrium
Cotton–mustard	−0.005	−0.004	−0.003	Quasi-equilibrium
Fallow-berseem	0.004	0.000	0.000	Quasi-equilibrium
Fallow-rice	0.011	−0.001	−0.000	Quasi-equilibrium
Fallow-sugarcane	−0.025	0.002	0.009	Quasi-equilibrium
Rice–berseem	−0.129	−0.241	0.067	Quasi-equilibrium
Rice–mustard	0.441	−0.196	−0.020	–
Rice–wheat	−0.740	−0.636	0.260	Still changing
Rice–wheat–berseem	0.076	0.025	0.157	Quasi-equilibrium
AESR 9.2				
Fallow-grass forest	0.015	−0.001	0.000	Quasi-equilibrium
Fallow-berseem	0.003	−0.001	−0.000	Quasi-equilibrium
Rice–berseem	0.114	−0.148	0.008	–
Rice–mustard	−0.218	–	–	–
Rice–wheat	12.899	−0.062	−0.190	Still changing
Rice–wheat–berseem	−0.001	−0.005	0.002	Quasi-equilibrium

N.B. AESR, agro-ecological sub-region.

management has changed substantially, but land use, in terms of agricultural crop production throughout the IGP, has not changed significantly over the 40-year period that this study attempts to characterize. The region has been in, and is expected to stay as, an intensive agricultural production system, with very little land moving out of production and vice versa.

The Century model suggests that the total SOC stocks for the region show a small increase from 1990 to 2000 following intensification of agricultural management associated with the Green Revolution (e.g. more tillage, less fallow). According to Century, the stock stabilized in the region around the year 2000 and is predicted to decline between 2000 and 2030. The trend towards greater intensification (with triple-cropping in many areas by 2030) could explain the cause of a predicted small decline in SOC between 2000 and 2030. Analysis of the cropping systems suggests some mechanisms for this change, as follows:

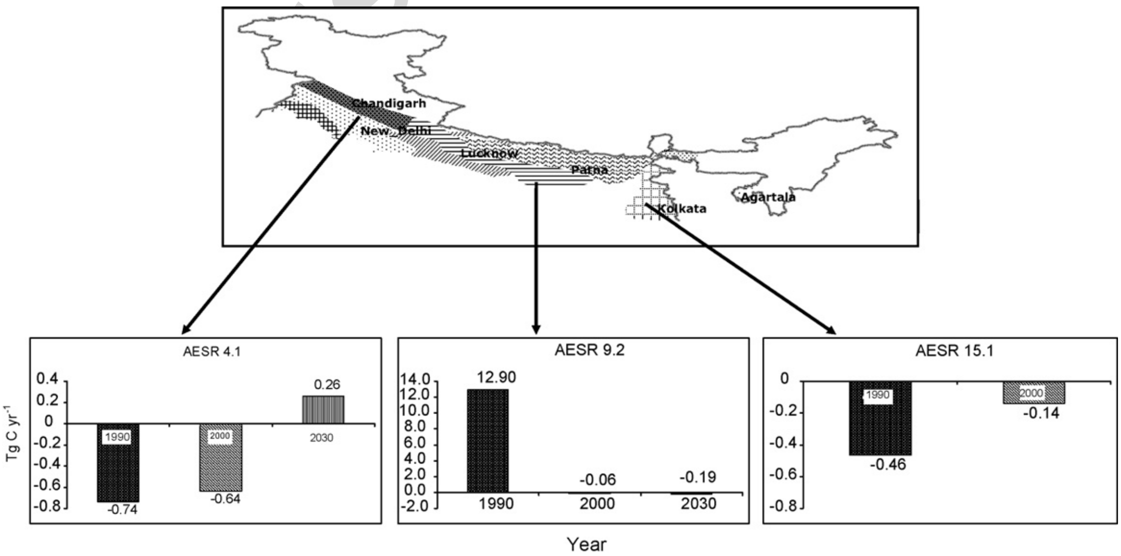

Fig. 7. Changes in SOC in the rice–wheat system across semi-arid (AESR 4.1) to humid (AESR 15.1) climate from 1990 to 2030 using the CENTURY output of the GEFSOC modelling system.

In most cases, the third crop grown in these systems is a short-season forage, vegetable, fibre or oilseed crop. This is grown between the rice and wheat crops. The crops largely tend to be low in production, particularly the vegetable and oilseed crops with low crop residue returns to the soil. Most of the above-ground biomass is removed at the time of harvest, when there is an additional round of intensive soil tillage operations (typically a mouldboard plough). If this third crop is a root crop, further soil disturbance will occur at the time of harvest.

Traditionally the eastern part of the IGP, India was a rice-growing area with very little wheat being cultivated. In contrast, in the north-western part wheat was the major cereal with very little area under rice. The Green Revolution introduced shorter duration, dwarf, photo insensitive, high yielding and fertilizer responsive varieties of wheat and rice. In addition to appropriate varietal developments, the development of irrigation facilities in the IGP was also responsible for the widespread adoption of the rice–wheat rotation (Kataki et al., 2001). In most of the cases the rice in rice–wheat rotations is grown under standing water. Some studies have shown submerged rice to enhance soil C status (Sahrawat et al., 2005). The agronomic conditions to grow rice and wheat have not only made the rice–wheat cropping system sustainable but also increased and/or stabilized the SOC stocks over the last 25 years. The Vision 2020, India document (Gupta, 2002) advocates bringing more areas under irrigation. If these projections become reality, more area under rice in submerged conditions could increase SOC stocks. The SOC stock estimated from soil survey data and the C-models support this contention. With the exception of a marginal dip in the SOC stock due to triple-cropping in some areas, most of the double-crop rotation areas, dominated by rice–wheat indicate an increasing trend in SOC. It seems, therefore, that a rice–wheat system may be able to sustain and maintain the C balance in these soils.

5. Conclusions

The soil mapping based approach indicates an increasing trend of SOC stock over the years. The GEFSOC modelling system suggests that SOC stocks under rice–wheat or rice–potato cropping systems in the lower IGP (towards West Bengal), had stabilized by 2000. Conversely, in the upper IGP (towards Punjab), the modelling system suggests that cropping rotations were still leading to increased SOC stocks in 2000. However, other trends in land management complicate the overall picture. Intensification of triple-cropping systems are likely to reduce SOC stocks. SOC losses under such systems might be reduced, mitigated or even improved by adopting reduced tillage or no-tillage systems.

A key question that has been raised during the IGP case study in this project is the sustainability of the rice–wheat crop production systems with respect to maintaining or increasing SOC stocks. The study of estimated SOC stocks and their changes indicate a quasi-equilibrium in organic C status in the soils of IGP, India. It thus shows that these soils, supporting rice and wheat as the dominant crops in India, are currently maintaining soil health in terms of organic C in soils.

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References

Abrol, I.P., Gupta, R.K., 1998. Indo-Gangetic Plains—issues of changing land use. In: LUCC Newsletter, March, 1998, Proc. GCTE-LUCC Science Conference. Barcelona, Catalonia, Spain, March 14–18, 1998, No. 1: 5–8 p. ISSN: 1137 5558-D.L.

Ajtay, G.L., Ketner, P., Duvigneaud, P., 1979. Terrestrial primary production and phytomass. In: Bolin, B., Degnes, E.T., Kempe, S., Ketner, P. (Eds.), The Global Carbon Cycle. John Wiley, Chichester, pp. 129–181.

Arrouays, D., Isabelle, V., Luckicin, J., 1995. Spatial analysis and modelling of top-soil carbon storage in temperate forest humic loamy soil of France. Soil Sci. 159, 191–198.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. Eur. J. Soil Sci. 47, 151–163.

Batjes, N.H., Sombroek, W.G., 1997. Possibilities for carbon sequestration in tropical and subtropical soils. Glob. Change Biol. 3, 161–173.

Batjes, N.H., Bhattacharyya, T., Mandal, C., Dijkshoorn, K., Pal, D.K., Milne, E., Gajbhiye, K.S., 2004. Soil data derived from SOTER for studies of carbon stocks and change in the Indo-Gangetic Plains (India) (ver. 1.0; GEFSOC Project). Report 2004/06. ISRIC—World Soil Information and NBSS&LUP (ICAR, India), Wageningen, 26 pp.

Batjes, N.H., Al-Adamat, R., Bhattacharyya, T., Bernoux, M., Cerri, C.E.P., Gicheru, P., Kamoni, P., Milne, E., Pal, D.K., Rawajfih, Z., 2007. Preparation of consistent soil data sets for modelling purposes: secondary SOTER data for four case study areas. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil carbon stocks at regional scales. Agric. Ecosyst. Environ. 122, 26–34.

Bhandari, A.L., Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., Gupta, R.K., 2002. Yield and soil nutrient changes in a long-term rice-wheat rotation in India. Soil Sci. Soc. Am. J. 66, 162–170.

Bhattacharyya, T., Pal, D.K., Velayutham, M., Chandran, P., Mandal, C., 2000. Total carbon stock in Indian soils: issues, priorities and management. In: Special Publication of the International Seminar on Land Resource Management for Food, Employment and Environment Security (ICLRM). Soil Conservation Society of India, New Delhi, pp. 1–46.

Bhattacharyya, T., Pal, D.K., Chandran, P., Mandal, C., Ray, S.K., Gupta, R.K., Gajbhiye, K.S., 2004. Managing Soil Carbon Stocks in the Indo-Gangetic Plains, India. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi 110 012, India, 44 pp.

Bhattacharyya, T., Easter, M., Paustian, K., Killian, K., Williams, S., Ray, S.K., Chandran, P., Durge, S.L., Pal, D.K., Gajbhiye, K.S., Milne, E., Singh B., 2005. Description of newly added crop database and modified crop files: Indo-Gangetic plains, India case study. Special publication for: Assessment of Soil Organic Carbon Stocks and Change at National Scale. NBSS & LUP, Nagpur, India, 196 pp.

Chandran, P., Bhattacharyya, T., Ray, S.K., Durge, S.L., Mandal, C., Sarkar, D., Sahoo, A.K., Singh, S.P., Ram, J., Gopal, R., Pal, D.K., Gajbhiye, K.S., Aurangabadker, B., Mendhekar, P., Singh, B., 2005. SOTER (Soil and Terrain Digital Databases) IGP, India. Special publication for: Assessment of Soil Organic Carbon Stocks and Change at National Scale. NBSS & LUP, Nagpur, India, 101 pp.

Chhabra, A., Patria, S., Dadhwal, V.K., 2003. Soil organic carbon pool in Indian forests. Forest Ecol. Manag. 173, 187–199.

Dadhwal, V.K., Nayak, S.R., 1993. A preliminary estimate of biogeochemical cycle of carbon for India. Sci. Cult. 59, 9–13.

Dickson, B.A., Crocker, R.L., 1953. A chronosequence of soils and vegetation near Nt. Stasta, California. I and II. Soil Sci. 4, 142–154.

Durge, S.L., Kamble, G.K., Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Sarkar, D., Sahoo, A.K., Singh, S.P., Ram, J., Gopal, R., Pal, D.K., Gajbhiye, K.S., Singh, B., 2005. A journey through the river Ganges to study the tropical paddy-wheat soils of Indo-Gangetic Plains, India. Special publication for: Assessment of Soil Organic Carbon Stocks and Change at National Scale. NBSS & LUP, Nagpur, India, 182 pp.

Easter, M., Paustian, K., Killian, K., Williams, S., Feng, T., Al Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Milne, E., Pal, D.K., Powlson, D.S., Rawajfih, Z., Sessay, M., Wokabi, S., 2007. The GEFSOC soil carbon modelling system: a tool for conducting regional-scale soil carbon inventories and assessing the impacts of land use change on soil carbon. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil carbon stocks at regional scales. Agric. Ecosyst. Environ. 122, 13–25.

Eswaran, H., Van Den Berg, E., Reich, P., 1993. Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57, 192–194.

Gupta, S.P. (Ed.), 2002. Report of the committee on India Vision 2020. Planning Commission of the Government of India, New Delhi, India.

Gupta, R.K., 2003. The rice-wheat consortium for the Indo-Gangetic Plains: vision and management structure. In: RWC-CIMMYT. (Ed.), Addressing Resource Conservation Issues in Rice-Wheat Systems of South Asia: A Resource Book. RWC-CIMMYT, New Delhi, India, ISBN 81-88572-00-4, pp. 1–7.

Gupta, R.K., Rao, D.L.N., 1994. Potential of wastelands for sequestering carbon by reforestation. Curr. Sci. India 66 (5), 378–380.

Jackson, M.L., 1973. Soil Chemical Analysis. Prentice Hall of India Ltd., New Delhi.

Jenny, H., 1950. Causes of high nitrogen and organic matter content of certain tropical forest soils. Soil Sci. 69, 63–69.

Jenny, H., Raychaudhuri, S.P., 1960. Effect of Climate and Cultivation on Nitrogen and Organic Matter Reserves in Indian Soils. ICAR, New Delhi, India, 126 pp.

Johnson, M.G., 1995. The role of soil management in sequestering soil carbon. In: Lal, R., Kimble, J.M., Follet, R.F., Stewart, B.A. (Eds.), Soil Management and Greenhouse Effects. Lewis Publishers, Boca Raton, FL, pp. 351–363.

Kataki, P.K., Hobbs, B.A., Adhikary, B., 2001. The rice wheat cropping system of south Asia: trends, constraints and productivity—a prologue. J. Crop Prod. 3, 1–26.

Mandal, C., Mandal, D.K., Srinivas, C.V., Sehgal, J., Velayutham, M., 1999. Soil Climatic Database for Crop Planning in India. NBSS&LUP, Nagpur, India, NBSS Publ. 53, 1014 pp.

Milne, E., Al-Adamat, R., Batjes, N.H., Bernoux, M., Bhattacharyya, T., Cerri, C.C., Cerri, C.E.P., Coleman, K., Easter, M., Falloon, P., Feller, C., Gicheru, P., Kamoni, P., Killian, K., Pal, D.K., Paustian, K., Powlson, D., Rawajfih, Z., Sessay, M., Williams, S., Wokabi, S., 2007. National and sub national assessments of soil organic carbon stocks and changes: the GEFSOC modelling system. In: Milne, E., Powlson, D.S., Cerri, C.E.P. (Eds.), Soil carbon stocks at regional scales. Agric. Ecosyst. Environ. 122, 3–12.

Naitam, R., Bhattacharyya, T., 2004. Quasi-equilibrium of organic carbon in swell-shrink soils of sub-humid tropics in India under forest, horticulture and agricultural system. Aust. J. Soil Res. 42, 181–188.

Pal, D.K., Srivastava, P., Durge, S.L., Bhattacharyya, T., 2003. Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangetic Plains, India. Catena 51, 3–31.

Ray, S.K., Chandran, P., Bhattacharyya, T., Durge, S.L., Mandal, C., Sarkar, D., Sahoo, A.K., Singh, S.P., Ram, J., Gopal, R., Pal, D.K., Gajbhiye, K.S., Singh, B., Aurangabadkar, B., 2004. Benchmark Soil Series of the Indo-Gangetic Plains (IGP), India. Special publication for: Assessment of Soil Organic Carbon Stocks and Change at National Scale. NBSS&LUP, Nagpur, India, 186 pp.

Sahrawat, K.L., 2006. Fresh water shortages and shortage for wetland rice cultivation. Curr. Sci. India 90 (11), 1458.

Sahrawat, K.L., Bhattacharyya, T., Wani, S.P., Chandran, P., Ray, S.K., Pal, D.K., Padmaja, K.V., 2005. Long-term lowland rice and arable cropping effects on carbon and nitrogen status of some semi-arid tropical soils. Curr. Sci. India 89 (12), 2159–2163.

Saikh, H., Varadachari, C., Ghosh, K., 1998. Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation: a case study in Simlipal National Park, India. Plant Soil 198, 137–145.

Saxena, A., Prasad, V., Singh, I.B., Chauhan, M.S., Hasan, R., 2006. On the Holocene record of phytoliths of wild and cultivated rice from Ganga Plain: evidence for rice-based agriculture. Curr. Sci. India 90 (11), 1547–1552.

Schlesinger, W.H., 1983. The world carbon pool in soil organic matter: a source of atmospheric carbon dioxide. In: Woodwell, G.M. (Ed.), The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurements by Remote Sensing. SCOPE Wiley, New York, pp. 111–127.

Soil Survey Staff, 2003. Keys to Soil Taxonomy, 9th ed. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC, USA.

Sombroek, W.G., Nachtergache, F.O., Habel, A., 1993. Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils. Ambio 22, 417–427.

Staff NBSS&LUP, 2002. Soils of India. National Bureau of Soil Survey and Land Use Planning, Nagpur, India, NBSS Publ. 94, 130 pp.+11 sheets maps.

Velayutham, M., Mandal, D.K., Mandal, C., Sehgal, J., 1999. Agro-Ecological Subregions of India for Development and Planning. National Bureau of Soil Survey and Land Use Planning, Nagpur, India, NBSS Publ. 35, 452 pp.

Velayutham, M., Pal, D.K., Bhattacharyya, T., 2000. Organic carbon stock in soils of India. In: Lal, R., Kimble, J.M., Stewart, B.A. (Eds.), Global Climate Change and Tropical Ecosystems. Lewis Publishers, Boca Raton, FL, pp. 71–96.