Agriculture, Ecosystems and Environment 144 (2011) 222–234

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Evaluation of RothC model using four Long Term Fertilizer Experiments in black soils, India

T. Bhattacharyya*, D.K. Pal, A.S. Deshmukh, R.R. Deshmukh, S.K. Ray, P. Chandran, C. Mandal, B. Telpande, A.M. Nimje, P. Tiwary

National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur 440010, Maharashtra, India

ARTICLE INFO

Article history:
Received 27 January 2011
Received in revised form 25 July 2011
Accepted 28 July 2011
Available online 24 September 2011

Keywords:
RothC
Oxidisable carbon content (Walkley and Black C)
Long Term Fertilizer Experiment
Soils
India

ABSTRACT

Carbon content in soils changes depending on the land use system, type of management practice and time. There is an increasing concern about the soil quality vis-à-vis organic carbon content in soils due to global warming and enhanced CO_2 concentration in the atmosphere. This has led to estimate carbon stock in soils at global and regional levels. The objective of the present study was to evaluate RothC model to estimate total organic carbon (TOC) changes under four long term fertilizer experimental sites representing sub-humid moist (Sarol and Nabibagh), sub-humid dry (Panjri) and semi-arid (Teligi) climate in India. The plant carbon input rate was calibrated using organic carbon and other soil parameters using RothC. The results showed that RothC could simulate changes in TOC in two contrasting eco-sites for surface soil layers. The root mean square error (RMSE) considered as modelling error ranged from 11.50 to 15.01, 4.70 to 11.60, 2.14 to 6.52 and 1.45 to 13.74 in the surface layers of Sarol, Nabibagh, Panjri, and Teligi sites, respectively. The simulation biases expressed by M (relative error) by Student'*t*' value for all the treatments at these sites were non-significant with two exceptions. Observed trends in TOC consist of an increase for all the four treatments in the sub-humid site of Sarol and Nabibagh; while manures alone or in combination increase TOC appreciably in Teligi and Panjri. TOC remained, however, almost similar over years for the control (no fertilizer or manure) and NPK treatments in all the four sites. Analysis of RothC output data showed that this model could be used as a tool to arrive at different threshold values of rainfall to influence decomposition rate modifier and thus to find out rate of organic carbon sequestration in various bioclimatic systems.

1. Introduction

Soil organic carbon (SOC) is vital for ecosystem function having a major influence on soil structure, water holding capacity, CEC and the soils' ability to form complexes with metal ions and store nutrients (Van Keulen, 2001). The knowledge of soil organic carbon in terms of its amount and quality is essential to sustain the quality and productivity of soils. In the recent past the greenhouse effect has created a great concern that has led to several studies on the qualities, kinds, distributions and behaviours of SOC (Eswaran et al., 1993; Sombroek et al., 1993; Batjes, 1996; Velayuthum et al., 2000). More recently soils and SOC have received attention in terms of the potential role they can play in mitigating the effect of elevated atmospheric CO_2. An understanding of SOC stocks and changes at the national and regional scale is necessary to further our understanding the global C cycle, to assess the responses of terrestrial ecosystem to climate change and to aid policy makers in making land use management decisions.

In the beginning of the 20th century, based on Rothamsted model, series of Long Term Fertilizer Experiments (LTFE) were established at different locations in India (Swarup and Wanjari, 2000). The purpose of LTFE at fixed sites in different agro ecological regions and on important cropping systems is not only to monitor the changes in yield responses in soil environment due to continuous application of plant nutrient inputs from fertilizers and organic sources, but also to help in the development of strategies and policies for rational fertilizer use management and in improvement in quality of soil and the environments. For developing fertilizer recommendations the focus of these experiments was to find out soil productivity. The amount of soil organic carbon is an important parameter to indicate soil productivity. Soil has been found

---

* Corresponding author at: Division of Soil Resource Studies, NBSS & LUP (ICAR), Amravati Road, Nagpur, 440010, India. Tel.: +91 0 712 2500545; fax: +91 712 2500534.

E-mail addresses: tapas11156@yahoo.com (T. Bhattacharyya), paldilip2001@yahoo.com (D.K. Pal), wini_deshmukh@rediffmail.com (A.S. Deshmukh), rups_desh@rediffmail.com (R.R. Deshmukh), skraysrs@yahoo.com (S.K. Ray), pchandran1960@yahoo.co.in (P. Chandran), champa_mandal@yahoo.co.in (C. Mandal), btelpande_78@rediffmail.com (B. Telpande), nimjeankush21@gmail.com (A.M. Nimje), ptiwary70@yahoo.co.in (P. Tiwary).

0167-8809/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2011.07.021

Table 1
Details of Long Term Fertilizer Experiment at Sarol, Madhya Pradesh, India.

Crop rotation	Treatment number	N:P:K application (kg ha^{-1})	Source of fertilizer	Crop yield (t ha^{-1})	
				Soybean	Safflower
Soybean–Safflower	T1	Control (No NPK and FYM)[a]	–	1.131	0.695
Soybean–Safflower	T2	N 20 (for soybean) and N 40 (for safflower)	Urea	1.628	1.132
Soybean–Safflower	T5	N 30 + FYM 6 t ha^{-1} (for soybean) and N 30 + FYM 6 t ha^{-1} (for safflower)	Urea	1.808	1.539
Soybean–Safflower	T7	N 30 + FYM 6 t ha^{-1} (for soybean) and N10–20 (for safflower)	Urea	1.913	1.692

Source: Sharma and Gupta (1993).

[a] FYM: Farm Yard Manure.

Table 2
Comparison of weather and soil datasets in Sarol, Nabibagh, Panjri and Teligi.

Soil depth (cm)	Rainfall, mm (month)[a]	ET[b], mm (month)	Clay (%)	MAR[c] mm	T_{max} °C[d]
Sarol (Sub-humid, moist)					
0–23	62.2 (June)	68.07(Oct) 14.87(Nov) 82.93(Dec)	62.7	1053	32.3
Nabibagh (Sub-humid, moist)					
0–23	39.26 (July)	52.35 (Oct)	50.7	1148	31.7
Panjri (Sub-humid, dry)					
0–23	40.23 (June)	53.64 (Nov)	56.5	1035	35.2
Teligi (Semi-arid, dry)					
0–23	61.72 (Sept)	63.65 (Nov) 18.29 (Dec) 81.94 (Jan)	57.74	505	33.4

[a] From weather file generated following soil moisture deficit values in RothC (Coleman and Jenkinson, 1999).

[b] ET: Evapotranspiration.

[c] MAR: Mean Annual Rainfall.

[d] Air Temperature.

to be both source and sink of carbon depending on management practices (Bhattacharyya et al., 2008).

Regional and global C budget quantification needs to include an understanding of SOC dynamics and SOC distribution at a regional level (Paustian et al., 1997). Carbon sequestration can be indirectly assessed through the modelling of SOC content, which may compliment direct measurement (Ardo and Olsson, 2003). Modelling offers an opportunity to study the future trends in soil carbon changes along with identifying areas with large potential for C sequestration. It thus helps in predicting and understanding future changes due to climate change, land use change and different land management conditions.

Table 3
Details of Long Term Fertilizer Experiment at Nabibagh, Madhya Pradesh, India.

Crop rotation	Treatment number	N:P:K application (kg ha^{-1})	Source of fertilizer	Crop yield (t ha^{-1})	
				Soybean	Wheat
Soybean–Wheat	T1	Control (No NPK and FYM)[a]	–	1.578	2.231
Soybean–Wheat	T2	N20: P60: K20 (GRD)[b] (for soybean) and N100: P50: K30 (GRD)(for wheat)	N (Urea) P(SSP)[f] K(MOP)[g]	2.056	2.895
Soybean–Wheat	T5	N12.5: P15: K10 + 5t FYM (for soybean) and N70: P30: K30 (for wheat)	N (Urea) P(SSP) K(MOP)	1.808	1.539
Soybean–Wheat	T6	N12.5: P15: K10 + 1t PM[c] (for soybean) and N70: P30: K30 (for wheat)	N (Urea) P(SSP) K(MOP)	2.090	3.381
Soybean–Wheat	T7	N12.5: P15: K10 + 5t UC[d] (for soybean) and N70: P30: K30 (for wheat)	N (Urea) P(SSP) K(MOP)	2.253	3.468
Soybean–Wheat	T10	5t WR[e] + 5t FYM (for soybean) and N70: P30: K30 (for wheat)	N (Urea) P(SSP) K(MOP)	1.848	2.928

Source: Singh et al. (2004).

[a] FYM: Farm Yard Manure.

[b] GRD: General Recommended Dose; NPK: Nitrogen, Phosphorus, And Potassium.

[c] PM: Poultry Manure.

[d] UC: Urban Compost.

[e] WR: Wheat Residues.

[f] SSP: Single Super Phosphate.

[g] MOP: Muriate of Potash.

Table 4
Details of Long Term Fertilizer Experiment at Panjri, Maharashtra, India.

Crop rotation	Treatment number	N^{a}:P^{b}:K^{c} application (kg ha^{-1})	Source of fertilizer
Cotton–Sorghum	T1	Control (No NPK and FYM^{d})	–
Cotton–Sorghum	T3	N60: P13: K0 (for cotton) and N60: P13: K0 (for sorghum)	N (Urea) P(SSP)
Cotton–Sorghum	T5	N0: P13: K25 + 10 t FYM (for cotton) and N0: P13: K25 + 10 t FYM (for sorghum)	N (Urea) P(SSP)
Cotton–Sorghum	T7	N30: P13: K25 (for cotton) and N30: P13: K25 + 5 t FYM (for sorghum)	N (Urea) P(SSP)
Cotton–Sorghum	T11	N0: P20: K38 + 15 t FYM (for cotton) and N0: P20: K38 + 15 t FYM (for sorghum)	N (Urea) P(SSP)

Source: Venugopalan and Pundarikakshudu (1999).
[a] N: Nitrogen.
[b] P: Phosphorus.
[c] K: Potassium.
[d] FYM: Farm Yard Manure.

Roth*C* is a soil organic carbon model that accounts for the effect of soil type, temperature, moisture content and plant cover on the turnover of organic carbon in soils. It is originally developed and parameterized to model the turnover of organic carbon in arable top soils from the Rothamsted long term field experiments and is basically concerned with soil processes (Coleman et al., 1997). In order to evaluate suitability for predicting changes on soil C stocks this model was tested under different environmental and management conditions. The study was undertaken with an object to simulate the SOC changes in four selected LTFE sites as influenced by diverse climatic factors and management practices in India.

2. Materials and methods

2.1. Experimental sites

The LTFE site of Sarol (Indore, Madhya Pradesh, India) represents soils developed in basaltic alluvial zone representing the Black Soil Region (BSR) of India. Sarol soil is a member of very fine, smectitic, hyperthermic Typic Haplusterts. These soils are formed in nearly level old flood plain. Typically, Sarol soils have very dark grayish brown, moderately alkaline, clayey A horizons and very dark grayish brown, moderately alkaline, clayey B horizons which are nearly 130–155 cm thick. The surface soil of the experimental site showed oxidisable (Walkley and Black, 1934) organic carbon of 7.0 g kg^{-1}, calcium carbonate equivalent 6.5%, bulk density 1.5 Mg m^{-3} and cation exchange capacity of 51.3 cmol (p^{+}) kg^{-1} (Murthy et al., 1982; Lal et al., 1994; Tamgadge et al., 1999). Soybean and safflower crops were grown annually in the College of Agriculture Farm, Indore, Madhya Pradesh during 1983 to 1985 (Lat. 22°36′52″ N, Long. 75°41′17″ E) (Table 1) (Sharma and Gupta, 1993). The climate is sub-humid moist with mean annual air temperature of 32.3 °C (mean annual maximum 34.8 °C) and mean annual rainfall of 1053 mm (Table 2) (Bhattacharyya et al., 2008). Fifty year mean monthly temperature (calculated from maximum and minimum monthly temperatures), and mean monthly rainfall were used for developing the weather files.

The LTFE site of Nabibagh represents a typical shrink–swell soil of the BSR. The Nabibagh soils belong to fine, smectitic, hyperthermic Typic Haplusterts (Murthy et al., 1982). These are clayey, moderately alkaline with organic carbon 8.0 g kg^{-1}, CEC 45.9 cmol (p^{+}) kg^{-1}, calcium carbonate equivalent 5.1%, and bulk density 1.3 Mg m^{-3} (0–15 cm) (NBSS and LUP Staff, 1994). Nabibagh LTFE was started during 2002 with a soybean–wheat cropping rotation at the Indian Institute of Soil Science farm in Bhopal, Madhya Pradesh and continued till 2005. Out of 12 treatments, we selected 6 treatments for the present study (Table 3) (Singh et al., 2004). This site represents sub-humid climate with mean annual maximum air temperature of 31.7 °C with mean annual rainfall of 1148 mm (Table 1). Fifty five years (1951–2006) monthly temperature (calculated from maximum and minimum monthly temperatures) and average rainfall were used to develop the weather files.

The Panjri soils belong to fine, smectitic, isohyperthermic Sodic Haplusterts. These soils are clayey, strongly alkaline with organic carbon 7.0 g kg^{-1}, CEC 63 cmol (p^{+}) kg^{-1}, calcium carbonate equivalent 4.8%, and bulk density ranging from 1.4 Mg m^{-3} (0–13 cm) to 1.6 Mg m^{-3} (13–38 cm). Panjri LTFE was started during 1986 with the cotton cropping system at the Central Institute for Cotton Research (CICR), Nagpur and continued till 1997. Out of eight treatments, we selected 5 treatments for the present study (Table 4) (Venugopalan and Pundarikakshudu, 1999). Panjri site represents sub-humid dry climate with mean annual maximum air

Table 5
Details of Long Term Fertilizer Experiment at Teligi, Karnataka, India.

Crop rotation	Treatment number	N:P:K application (kg ha^{-1})	Source of fertilizer
Rice (Kharif)- Rice (Rabi)	T1	Control (No NPK and FYM)	–
Rice (Kharif)- Rice (Rabi)	T2	N60: P30: K30 (for kharif rice) and N60: P30: K30 (for rabi rice)	N (Urea) P(SSP) K(MOP)
Rice (Kharif)- Rice (Rabi)	T6	N60: P30: K30 + CDS^{a} 6 t ha^{-1}(for kharif rice) and N120: P60: K60 (for rabi rice)	N (Urea) P(SSP) K(MOP)
Rice (Kharif)- Rice (Rabi)	T8	N60: P30: K30 + PS^{b} 10 t ha^{-1}(for kharif rice) and N120: P60: K60 (for rabi rice)	N (Urea) P(SSP) K(MOP)
Rice (Kharif)- Rice (Rabi)	T10	N60: P30: K30 + *Gliricidia* 6 t ha^{-1}(for kharif rice) and N120: P60: K60 (for rabi rice)	P(SSP) K(MOP)

Source: Bellaki et al. (1998).
[a] CDS: Cowdung slurry.
[b] PS: Paddy straw.

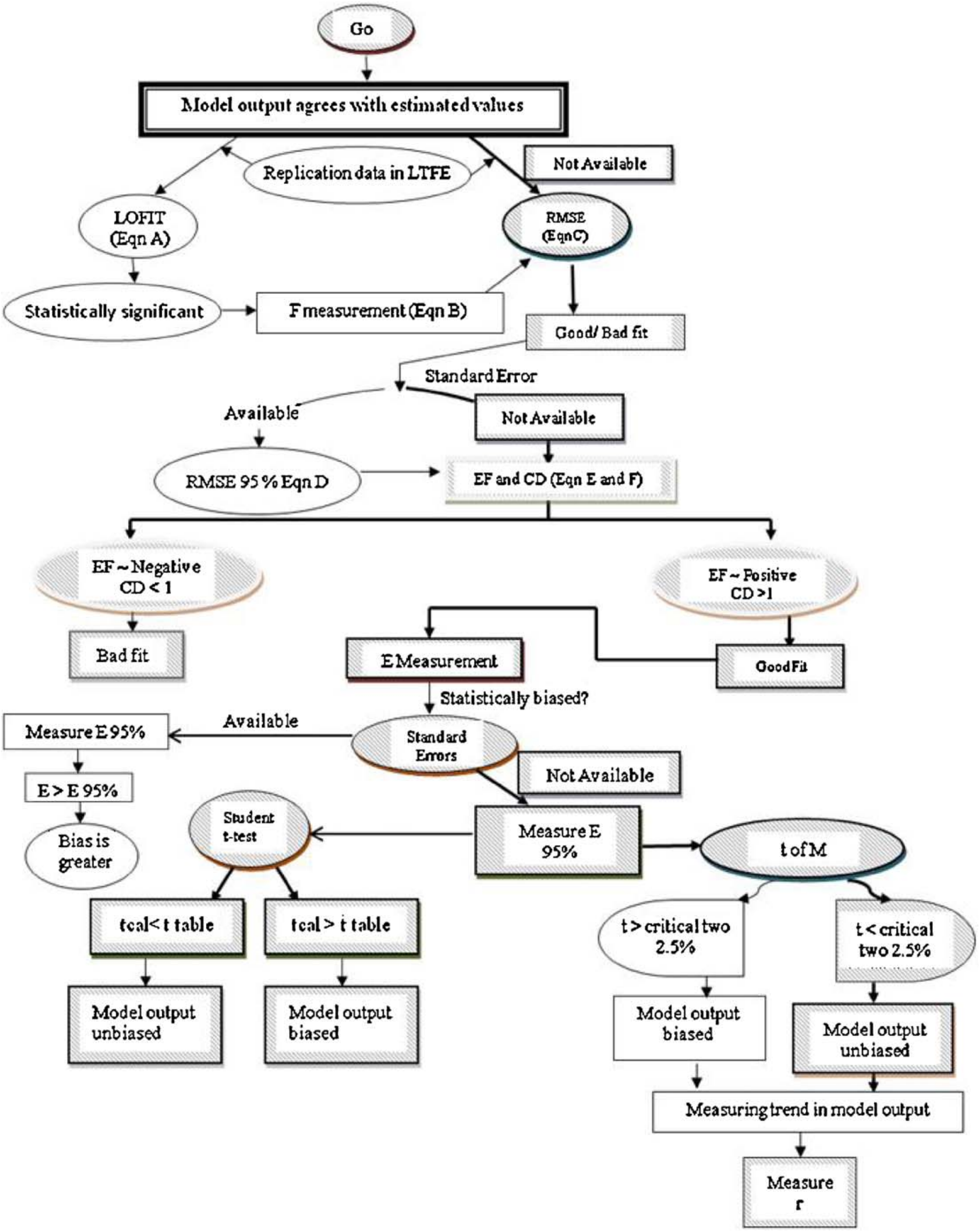


Fig. 1. Quantitative comparison between predicted and modelled soil organic carbon – a statistical scheme (hatched tracks) were followed in our study. For Eqs. A to F please see Smith et al. (1997).

temperature of 35.2 °C with mean annual rainfall of 1035 mm (Table 2). Information on fifty five years' (1951–2006) monthly temperature (calculated from maximum and minimum monthly temperatures) and average rainfall was used to develop the weather files.

The LTFE site of Teligi represents a typical shrink–swell soil of the BSR. The Teligi soils belong to fine, smectitic, isohyperthermic Sodic Haplusterts (Bhattacharyya et al., 2008). These are clayey, strongly alkaline with organic carbon 15.0 g kg^{-1}, CEC 51.4 cmol (p^+) kg^{-1}, calcium carbonate equivalent 10.5%, and bulk density ranging from 1.2 Mg m^{-3} (0–10 cm) to 1.5 Mg m^{-3} (10–25 cm) (Barde et al., 1974). Teligi LTFE was started during 1984 and continued till 1994 with the rice (Kharif and Rabi) cropping system at Agriculture Research Station, Siruguppa, Karnataka and continued till 1994. Out of 12 treatments, we selected 5 treatments for the present study (Table 5) (Bellaki et al., 1998). Teligi site represents semi-arid dry climate with mean annual maximum air temperature of 33.4 °C with mean annual rainfall of 505 mm (Table 1). Fifty five year (1951–2006) monthly temperature (calculated from maximum and minimum monthly temperatures) and average rainfall were used to develop the weather files.

2.2. Model description and evaluation

RothC-26.3 is a model for the turnover of organic carbon and top soils that allows for capturing the effects of soil type, temperature, moisture content and plant cover on the turnover process. In RothC model soil organic carbon is split into four compartments

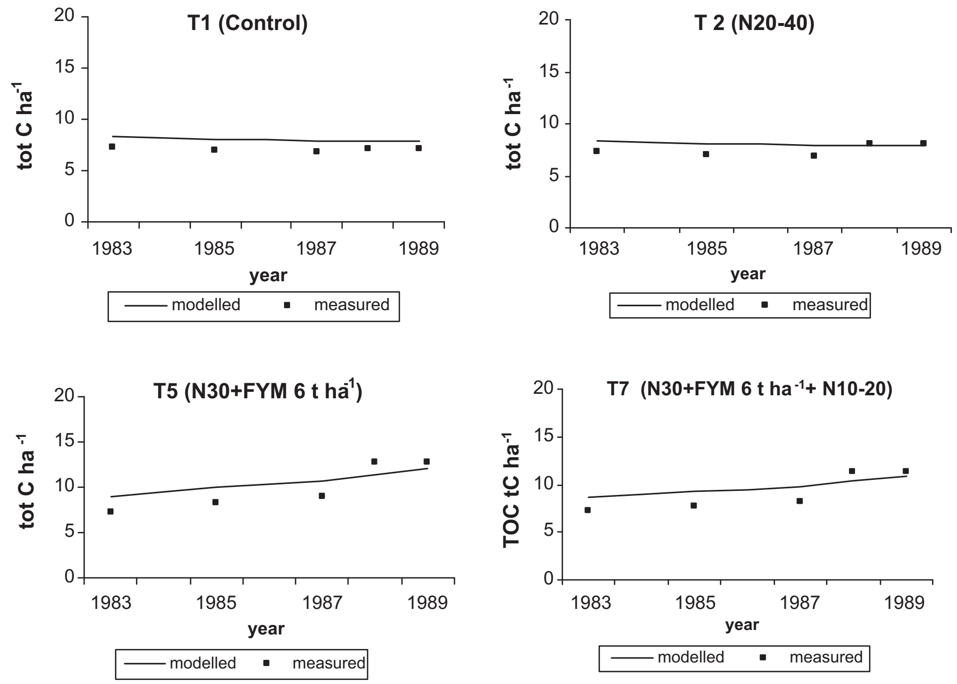


Fig. 2. Modelled organic carbon contents of the surface horizon (0–23 cm) of soils from four treatments on the LTFE site of Sarol. C inputs: before 1983 a plant carbon return of 0.75 t C ha^{-1} yr^{-1} was used which gives a starting equilibrium C content of 10.35 t C ha^{-1} using a clay content of 62.7% and the soil depth interval of 23 cm with the calculated IOM content of 0.70 t C ha^{-1}. After 1983, T2 (N20–40) received 0.63 t C ha^{-1} yr^{-1} as plant C returns T5 (N30 + FYM) and T7 (N30 FYM + N10–20) received 1.41 and 1.40 t C ha^{-1} yr^{-1}, respectively with additional 3.33 FYM ha^{-1} in May every year. The DPM/RPM ratio used was 1.44 for 1983 onwards, the usual value for agricultural crops. Previous to 1983 it was 0.25 used for deciduous forest species in the semi-arid tropics. Since 1983 two crops (soybean and safflower) were grown keeping the ground covered for ten months leaving May and June as fallow months. To find out the projected TOC (beyond 1988) we presumed same plant inputs, IOM and other parameters as used for the treatments during 1983–1988.

such as decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). Besides there is also a small amount of inert organic matter (IOM) which is resistant to decomposition. The relative proportion of DPM and RPM depends on the type of vegetation. The model is programmed to a value of 59% DPM and 41% RPM for the agricultural crops and improved grassland. These values differ depending on type of the vegetation. It uses a monthly time step to calculate total organic carbon (t ha^{-1}), microbial biomass carbon (t ha^{-1}) and ^{14}C (from which the equivalent radiocarbon age of the soil can be calculated) on years to centuries timescale (Jenkinson et al., 1992; Jenkinson and Coleman, 1994). It needs few inputs and

Table 6
TOC and its turnover in different treatments over years in Sarol, Nabibagh, Panjri and Teligi.

Treatments	Values in t ha^{-1}			
	Year 1990	2010	2030	2050
Sarol, Madhya Pradesh, India				
T1 (Control, No fertilizer and FYM)	7.80	7.60 (−3)[a]	7.52 (−4)	7.47 (−4)
T2 (N20-40)	8.80	10.73 (22)	11.92 (35)	12.763 (45)
T5 (N30 + FYM)	12.58	16.17 (29)	22.81 (81)	25.70 (104)
T7 (N30FYM + N10-20)	11.32	14.23 (26)	19.48 (72)	21.76 (92)
Nabibagh, Madhya Pradesh, India				
T1 (Control, No fertilizer and FYM)	12.92	12.47 (−3)	12.38 (0)	12.34 (3)
T2 (N:P:K = 20:60:20)	13.31	13.12 (1)	13.42 (3)	13.63 (6)
T5 (N:P:K = 12.2:15:10 + FYM)	14.85	16.86 (28)	20.23 (68)	22.44 (96)
T6 (N:P:K = 12.2:15:10 + PM)	13.20	15.35 (30)	17.45 (65)	21.86 (89)
T7 (N:P:K = 12.2:15:10 + UC)	13.51	17.85 (70)	28.79 (174)	35.93 (242)
T10 (WR + 5t FYM + N:P:K)	14.50	15.77 (60)	18.13 (141)	19.68 (195)
Panjri, Nagpur, Maharashtra				
T1 (Control, No fertilizer and FYM)	15.60	15.58 (−2)	15.57 (−2)	15.60 (−2)
T3 (N:P:K = 60:13:0)	15.57	15.68 (1)	15.74 (1)	15.57 (-1)
T5 (N:P:K = 0:13:25 + FYM)	27.68	32.70 (65)	35.91 (82)	27.68 (40)
T7 (N:P:K = 30:13:25 + FYM)	20.54	28.11 (37)	32.86 (60)	35.89 (75)
T11 (N:P:K = 0:20:38 + FYM)	19.21	27.49 (43)	32.80 (71)	36.18 (88)
Teligi, Karnataka, India				
T1 (Control, No fertilizer and FYM)	10.66	10.99 (3)	10.88 (2)	10.80 (1)
T2 ($N:P_2O_5:K_2O$ = 60:30:30)	10.67	11.43 (7)	11.94 (12)	12.3 (15)
T6 ($N:P_2O_5:K_2O$ = 60:30:30 + CDS)	13.14	16.10 (22)	18.18 (38)	19.64 (49)
T8 ($N:P_2O_5:K_2O$ = 60:30:30 + PS)	12.07	17.69 (47)	21.11 (75)	23.48 (95)
T10 ($N:P_2O_5:K_2O$ = 60:30:30 + *Gliricidia*)	12.54	19.77 (58)	24.14 (93)	27.18 (117)

[a] Parentheses indicate percentage changes compared to 1990 for Sarol, Teligi, Panjri and 2002 for Nabibagh for 0–23 cm soil depth.

Table 7
Model errors and simulation bias for four experimental sites.

Treatments	Simulation error					Simulation bias		
	RMSE (%)	r	M	t Value of M[a]	Student t[b]	Critical t value (at two tailed)	Significance of bias (yes/no)[c]	Significance of bias (yes/no)[d]
Sarol								
T1 (Control, No fertilizer and FYM)	13.88	0.34	−0.96	0.28	8.67	2.31	No	Yes
T2 (N20-40)	11.50	0.76	−0.58	0.16	2.12	2.31	No	No
T5 (N30 + FYM)	15.01	0.94	−0.68	0.67	0.54	2.31	No	No
T7 (N30FYM + N10-20)	13.64	0.93	−0.58	0.028	0.59	2.31	No	No
Nabibagh								
T1 (Control, No fertilizer and FYM)	7.33	0.11	−0.808	0.27	4.39	2.31	No	Yes
T2 (N:P:K = 20:60:20)	9.32	0.72	−0.44	0.05	0.87	2.31	No	No
T5 (N:P:K = 12.2:15:10 + FYM)	4.70	0.97	−0.41	0.35	0.61	2.31	No	No
T6 (N:P:K = 12.2:15:10 + PM)	8.03	0.88	−0.692	0.07	1.29	2.31	No	No
T7 (N:P:K = 12.2:15:10 + UC)	11.60	0.92	−1.45	0.16	0.64	2.31	No	No
T10 (WR + 5t FYM + N:P:K)	8.40	0.86	−0.98	0.21	1.51	2.31	No	No
Panjri								
T1 (Control, No fertilizer and FYM)	2.14	0.78	−0.30	0.65	0.94	2.31	No	No
T3 (N:P:K = 60:13:0)	5.71	0.98	−0.93	0.21	1.03	2.31	No	No
T5 (N:P:K = 0:13:25 + FYM)	6.52	0.90	−0.97	0.22	1.19	2.31	No	No
T7 (N:P:K = 30:13:25 + FYM)	6.10	0.99	−0.56	0.14	0.56	2.31	No	No
T11 (N:P:K = 0:20:38 + FYM)	6.11	0.84	−0.92	0.24	1.38	2.31	No	No
Teligi								
T1(Control, No fertilizer and FYM)	1.45	0.22	−0.11	−1.03	−2.12	2.31	No	No
T2 ($N:P_2O_5:K_2O = 60:30:30$)	3.75	0.83	−0.12	0.14	0.70	2.31	No	No
T6 ($N:P_2O_5:K_2O = 60:30:30$ + CDS)	6.55	0.97	−0.796	0.33	1.17	2.31	No	No
T8 ($N:P_2O_5:K_2O = 60:30:30$ + PS)	8.23	0.90	−0.630	1.16	1.57	2.31	No	No
T10 ($N:P_2O_5:K_2O = 60:30:30$ + *Gliricidia*)	13.74	0.87	−0.33	0.02	0.38	2.31	No	No

[a] t value of $M = \left[t = \frac{\Sigma D}{n\Sigma D^2 - (\Sigma D)^2/n-1} \right]$.

[b] Student $t = \frac{\text{Mean of measured values} - \text{Mean of modelled values}}{\sqrt{\text{Variance of observed value} + \text{Variance of modelled values}/n}}$.

[c] On the basis of 't' of M.

[d] On the basis of Student 't' value.

those are easily obtainable. Roth*C* is designed to run in two modes: 'forward' in which known inputs are used to calculate changes in soil organic matter and 'inverse', when inputs are calculated from known changes in soil organic matter. Mean monthly air temperature (MAT) and mean annual rainfall (MAR) were estimated from the nearest standard meteorological station for each site. Since open pan evaporation (PE) data were not available, mean monthly potential evapotranspiration (PET) was used (Mandal et al., 1999) to convert to open pan evaporation assuming PE = PET/0.75. Soil moisture deficit (SMD) was calculated for the surface horizons of the soils. Using SMD data, weather files for each layer were created following the method of Coleman and Jenkinson (1999).

2.3. Parametrization of the model

The ability of the Roth*C* model to predict change in TOC turnover depends on the rate modifying factors viz temperature and moisture. The meteorological datasets provide only air temperature. We have modified the air temperature to soil temperature while developing the weather files. Besides in the northern hemisphere the Roth*C* starts since January. In the humid tropical climate like India we have parametrized the Roth*C* so that it starts with the onset of monsoon in the month of June/July. We made changes to suit the climate of the various LTFE we tried in this study.

Soil systems attain a steady-state (quasi-equilibrium) after accumulation of dry matter as well as loss of TOC over time. Depending on land use system, SOC levels often show tooth like cycles of accumulation and loss (Batjes, 2001). After each change in land use system, a period of constant management is required to reach a new quasi-equilibrium (QEV) stage. In this way the SOC is stabilized to another QEV characteristic of that changed situations in terms of new land use pattern, vegetation cover and management practice. It has been reported that under natural vegetation SOC values tend to attain QEVs with varying durations of 500–1000 years in a forest system (Jenny, 1950; Dickson and Crocker, 1953), 30–50 years in agricultural systems after forest cutting (Arrouyas et al., 1995; Johnson, 1995; Batjes, 2001) and 5–15 years in agriculture systems in other Indian soils (Saikh et al., 1998; Naitam and Bhattacharyya, 2004; Chandran et al., 2009). In the present study, Sarol (1983–1988), Panjri (1986–1997), Teligi (1984–1994) satisfy the minimum numbers of years for attaining equilibrium except for Nabibagh LTFE (2002–2005). It may however be mentioned here that before the initialization of LTFE trials, soybean–wheat crop rotation was followed since 1992. As a matter of fact, Indian Institute of Soil Science, Bhopal, India conducted field experiments since 1992–1993 with soybean–wheat crop rotation (Rao and Shrivastava, 1998). We did not get those data in order for Roth*C* modelling and so we used the datasets during the period of 2002–2005. In effect, therefore, the same site of Nabibagh is stabilized with soybean–wheat since 1992 and thus has reached a stage of equilibrium. It seems, therefore, that all the LTFE sites selected and the assumptions for the steady state vis-à-vis equilibrium is in place.

2.4. Calibration of the model

To fit the model to the data collected from these four LTFE sites, the necessary first step was to run Roth*C* with an annual input of organic carbon that had been selected iteratively to give the TOC at the start of each experiment. We followed this step for each site. When TOC was set at the beginning, the model was run for the selected treatments using iteratively selected values for the annual return of plant carbon to the soil.

Soil clay (%), BD ($Mg\ m^{-3}$) and TOC were utilized as model inputs (0–20 cm) for each benchmark spot. Since we did not have radiocarbon values (^{14}C), the equation derived by Falloon et al. (2002) was used ($IOM = 0.049/SOC^{1.139}$) to estimate the size of the IOM

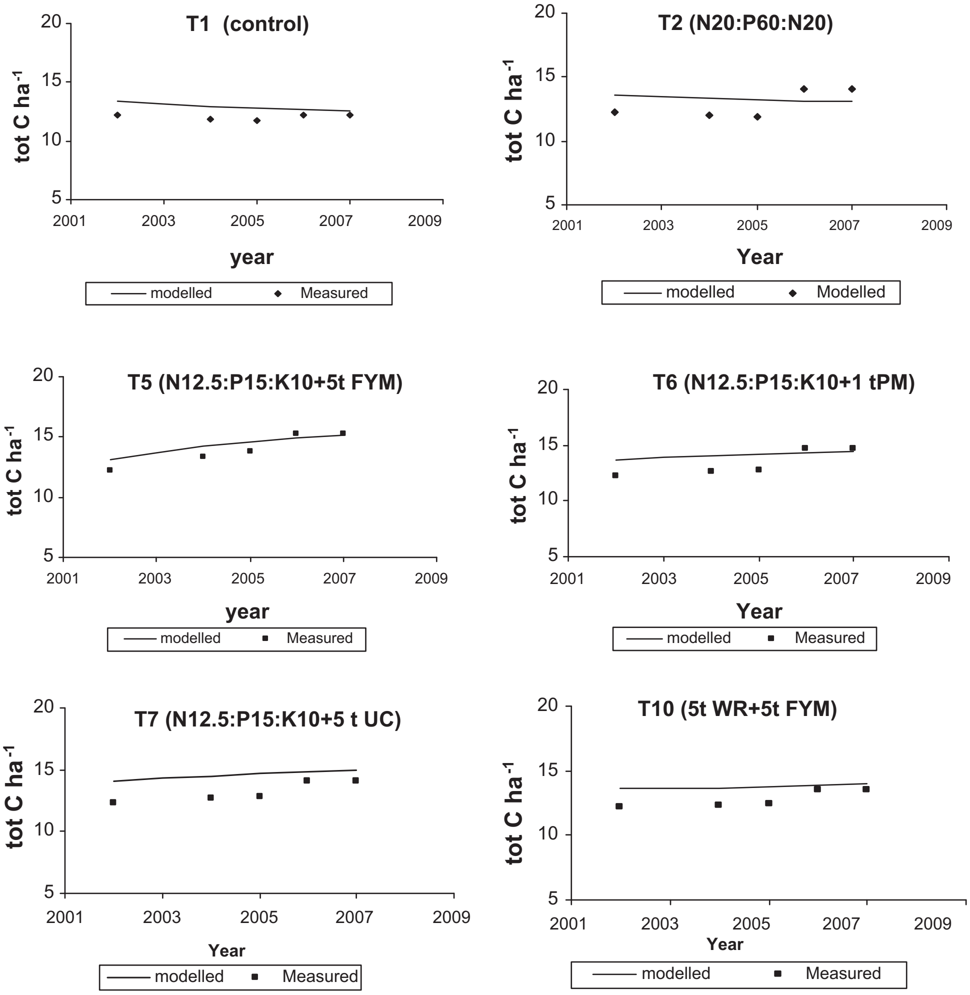


Fig. 3. Modelled organic carbon contents of the surface horizon (0–23 cm) of soils from six treatments on the LTFE site of Nabibagh. C inputs: before 2002 a plant carbon return of 0.70 t C ha^{-1} yr^{-1} was used which gives 1.27 t C ha^{-1} using a clay content of 52.20% and the soil depth interval of 23 cm with the calculated IOM content of 0.85 t C ha^{-1}. After 2002, T2 General Recommended Dose (GRD) received 0.99 t C ha^{-1}, T5 and T6 (NPK + organic plots) received same 1.09 t C ha^{-1} yr^{-1} as plant C returns with additional 3.33 for FYM and PM; T7 (NPK + UC) received 1.39 and T10 (NPK + organic plots) received 1.45 t C ha^{-1} yr^{-1} which includes contribution of farm yard manure every year during July. The DPM/RPM ratio used was 1.44 for 2002 onwards, the usual value for agricultural crops. Previous to 2002 it was 0.67 used for unimproved grasslands in the Black Soil Regions (BSR), India. Since 2002 two crops (soybean and wheat) were grown keeping the ground covered for ten months leaving May and June as fallow months. To find out the projected TOC (beyond 2006) we presumed same plant inputs, IOM and other parameters as used for the treatments during 2002–2006.

pool from total SOC content. We decided to estimate appropriate plant carbon input rates (PI t C ha^{-1} yr^{-1}) with fertilizer and other management in each LTFE site. We used the same specific carbon input rate for a set of crops for a treatment of a particular LTFE site for all the years of simulation. It is in view of this we had set the initial IOM (t C ha^{-1}) value and adjusted the annual PI rate of carbon through iterative process for arriving at the best agreement between measured and modelled TOC values. The IOM values for LTFE sites were set accordingly as 0.7 (Sarol), 0.85 (Nabibagh), 1.25 (Panjri), and 1.25 (Teligi).

Organic matter decomposition rates were calculated from the maximum decomposition rate constants ($k_{pool\,n}$) for each pool (1 to n). Total SOC and the SOC concentration in each of the model pools in the final year of simulation are shown in Eqs. (i) and (ii).

$$\text{SOC decomposition rate} = \sum_{n}^{1}\left(\frac{\text{SOC pool } n}{\text{Total SOC}} X\, k\, \text{pool } n\right) \qquad \text{(i)}$$

$$\text{Modified SOC Decomposition rate} = \text{SOC Decomposition rate} \times \text{Rate modifier product sum} \qquad \text{(ii)}$$

2.5. Validation of the model

The model performance was evaluated using various statistical parameters such as (i) r: simulation correlation coefficient; (ii) RMSE: root mean square error measuring total simulation error; (iii) M: mean difference or differences between means of predicted and measured values exploring the total simulation bias; (iv) t of M: a lower value of t of M than the critical two-tailed 2.5% t value means the model bias is not significant, that is the simulation bias is acceptable (Smith et al., 1996, 1997; Guo et al., 2006). We also measured Student's t to find out simulation bias as explained later.

To assess the impact of global change on TOC and subsequent feedback effects soil organic matter models have been used. A model's simulation of future events obviously cannot be compared to measured data to verify its validity. We can, however, get some measure of performance by testing a model's ability to simulate long-term soil organic matter changes using existing datasets. The primary purpose of this exercise then is to test the ability of soil carbon models to simulate the long term dynamics of soil organic matter under a variety of land use systems in different types of bioclimate with varying rainfall pattern as a mean of identifying

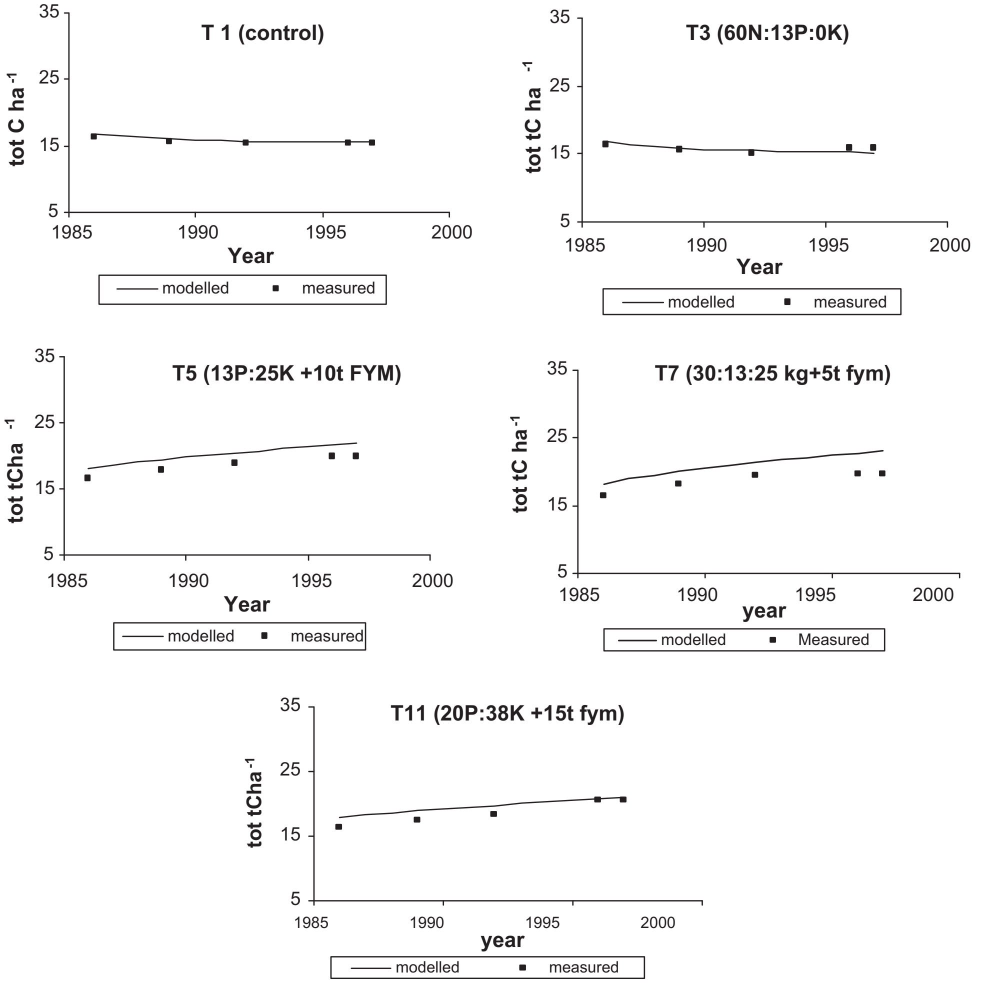


Fig. 4. Modelled organic carbon contents of the surface horizon (0–23 cm) of soils from eight treatments on the LTFE site of CICR, Panjri farm, Nagpur. C inputs: before 1986 a plant carbon return of 1.70 t C ha^{-1} yr^{-1} was used which gives a starting equilibrium C content of 17.24 t C ha^{-1} using a clay content of 56.5% and the soil depth interval of 23 cm with the calculated IOM content of 1.25 t C ha^{-1}. After 1986, T3 (N 60: P 13 kg) received 1.15 t C ha^{-1} yr^{-1} as plant C returns; T5 (P13:25K kg + 10 t FYM) received 1.36 and T7 (30N: 13P: 25K + 5 t FYM), T11 (20P: 38K + 15 t FYM) received 0.66, 1.02 t C ha^{-1} yr^{-1}, respectively with an average additional 2.34 FYM ha^{-1} in May every year. The DPM/RPM ratio used was 1.44 for 1986 onwards, the usual value for agricultural crops. Previous to 1986 it was 0.25 used for deciduous forest species in the semi-arid tropics. Since 1986 two crops (cotton and sorghum) were grown keeping the ground covered for ten months.

which model is likely to be most appropriate to future global change impact assessment in different environments (Smith et al., 1997).

In the present study we selected RothC model to predict variables *viz* total organic carbon. Our exercise is restricted to the ability of the model to simulate the long term changes in total organic carbon content. A schematic representation of statistical steps for evaluating the accuracy of a simulation and determination of acceptable error is shown in Fig. 1.

3. Results

3.1. Performance of model and plant C input in northern black soil region

Sarol site was modelled for the surface horizon (0–23 cm). The LTFE data indicated that TOC marginally increased when organic carbon is externally added through inorganic fertilizers (T2, Fig. 2) when compared with control (T1, Fig. 2). Rapid increase in TOC in T5 and T7 (Fig. 2) was observed due to the addition of FYM in combination with inorganic fertilizer (Fig. 2). Regular application of NPK increased TOC slightly (T2, Fig. 2). Addition of inorganic fertilizers alone did not bring an appreciable increase in TOC content over years. Usually the harvesting of annual crops is done almost from the ground level. The grain and straw both are used although for different purposes. The stubbles are removed before sowing the next crop. This gives very little scope of returning the biomass back to soil. This happened in cases when higher inorganic fertilizer is added; yield increased but SOC did not change much. This is in contrast to the treatments where organic amendments are applied along with the inorganics. The manures, since get mixed with soils, help in increasing the SOC content.

Inorganic fertilizer in combination with organic in T5 and T7 brought appreciable increase in TOC. RothC registered an increase in TOC beyond 1990 when compared with the control in Sarol (Table 6). The total simulation error in terms of RMSE in Sarol ranged from 11.50 to 15.01% (Table 7). The simulation bias expressed by *M* was found to be not significant for all the treatments since the *t* values were lower than the critical 2.5% two-tailed *t*-value. We also evaluated the simulation bias using Student's *t* values. We had similar experience as of *t* value of *M* for all the treatments of Sarol except T1 (Table 7). The simulation correlation coefficient (*r*) for T1 supports this observation indicating a significant difference between modelled and measured values (Table 7).

The average grain yield of four treatments at Sarol site during the experimental period (Table 1) showed that T2 (N20–40), T5 (N30 + FYM) and T7 (N30 FYM + N10–20) brought significant changes in soybean and safflower yield. A close look at yield data

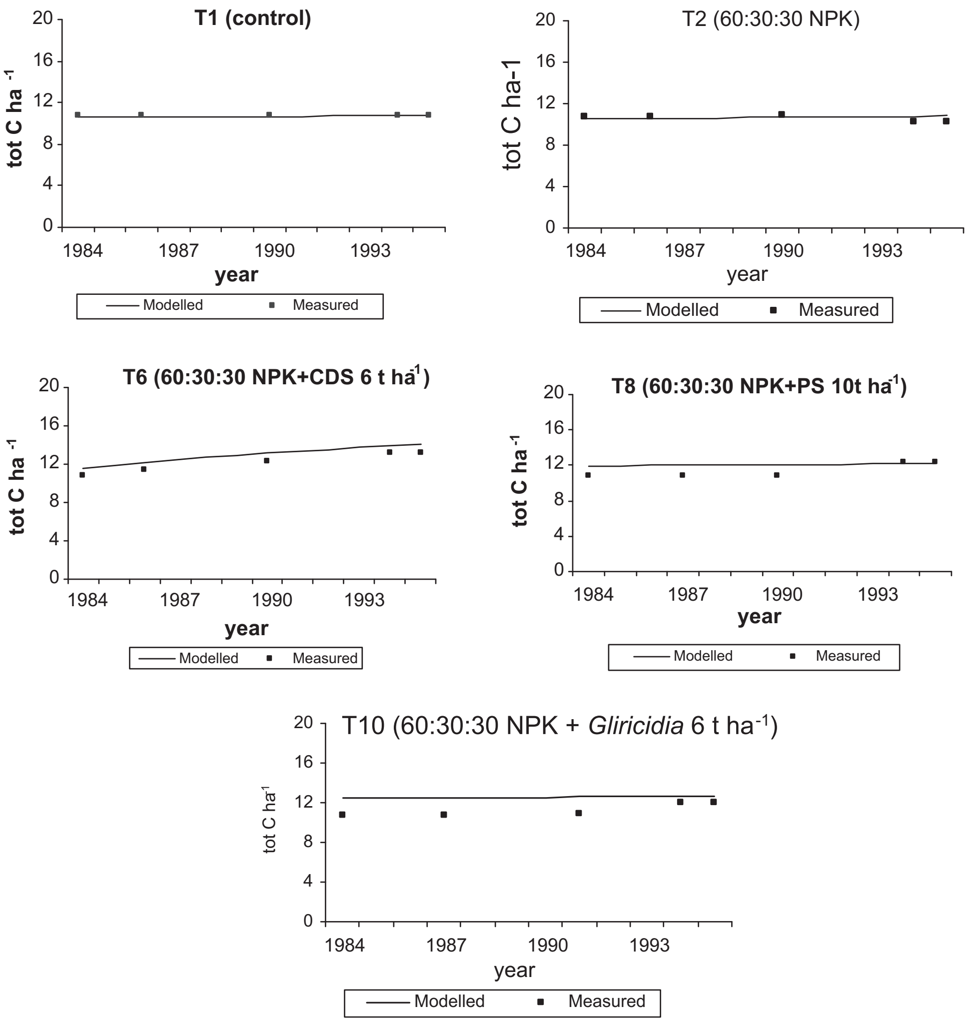


Fig. 5. Modelled organic carbon contents of the first horizon (0–23 cm) of soils from five treatments on the LTFE site of Teligi. C inputs: before 1984 a plant carbon return of 0.86 t C ha^{-1} yr^{-1} was used which gives 10.35 t C ha^{-1} using a clay content of 57.74% and the soil depth interval of 23 cm with the calculated IOM content of 1.25 t C ha^{-1}. After 1984, T2 (NPK plot) and T6 (NPK + organic plots) received 5.18 t C ha^{-1} yr^{-1} as plant C returns with additional 1.875 for cow dung slurry; T8 received 5.20 and T10 (NPK + organic plots) received 3.68 t C ha^{-1} yr^{-1} which includes contribution of paddy straw (T8) and *Gliricidia* (T10) every year during July. The DPM/RPM ratio used was 1.44 for 1984 onwards, the usual value for agricultural crops. Previous to 1984 it was 0.67 used for unimproved grasslands in Black Soil Regions (BSR), India. Since 1986 two crops (paddy and wheat) were grown keeping the ground covered for ten months leaving May and June as fallow months. To find out the projected TOC (beyond 2004) we presumed same plant inputs, IOM and other parameters as used for the treatments during 1984–1995.

(Table 1) and TOC (Table 6) indicated that application of only inorganic fertilizer (T2) did not increase TOC but increased crop yield while application of inorganic fertilizer in combination with organic materials (T5 and T7) brought increase in TOC as well as crop yield. Estimated plant carbon input rates (0–23 cm) were 0.59 t C ha^{-1} yr^{-1} for control and 0.63 t C ha^{-1} yr^{-1} in plots receiving N (20–40). These values were 1.41 and 1.40 for T5 (N30 + FYM) and T7 (N30 FYM + N10–20), respectively. Increased plant carbon input rates for these treatments showed the effect of addition of external sources of plant nutrients to increase biomass carbon.

3.2. Performance of model and plant C input in central black soil region

Nabibagh site was modelled for the surface horizon (0–23 cm). Nabibagh LTFE data indicated that TOC marginally increased when organic carbon is externally added along with the inorganic fertilizers (T2, Fig. 2) when compared with control (T1, Fig. 2). Rapid increase in TOC in treatments T5, T6, T7 and T10 (Fig. 2) is seen due to the addition of FYM and other organic substances like paddy straw (PS), urban compost (UC), *Gliricidia*, wheat residue (WR) in combination with inorganic fertilizer (Fig. 2). Regular application of NPK increases TOC in T2 (Fig. 3).

Roth*C* registered an increase in TOC beyond 1985 when compared with the control (Table 6). Addition of organics further aided in increasing TOC. Taking 1990 as the base year, relative increase in TOC was high in T2 (GRD) followed by T5 (NPK + FYM), T6 (NPK + PM), T7 (NPK + UC) and T10 (WR + FYM + NPK) respectively. Poultry manure (PM) in T6 had little effect on TOC increase (Table 6, Fig. 3).

The total simulation error in terms of RMSE in Nabibagh range from 4.70 to 11.60% (Table 7). The simulation bias expressed by M was found to be not significant for all the treatments since the t values were lower than the critical 2.5% two-tailed *t*-value. However simulation bias was significant in T1 when it was evaluated on the basis Student *t* values. Poor *r* value of 0.11 in T1 supports this observation (Table 7). The simulation correlation coefficient (*r*) ranged between 0.98 and 0.99.

The average grain yield of six treatments at Nabibagh site during the experimental period is shown in Table 3. A close look at yield data and TOC (Table 4) indicate that application of only inorganic fertilizer (T2) does not increase TOC but increases crop yield, while application of inorganic fertilizer in combination with organics (treatments T5, T6, T7 and T10) brings an increase in TOC as well as crop yield.

Panjri data showed that when organic carbon was added through farm yard manure (T5, T7 and T11), there was an effective increase in TOC (Table 5; Fig. 4). It was also observed that a regular application of NPK (T2, Table 5) marginally influences TOC during the experimental period (1986–1997) (Fig. 4).

There was a noticeable increase in TOC content after addition of inorganic fertilizer in combination with farm yard manure (Fig. 5). Roth*C* registered an increase in TOC beyond experimental period when compared with control. Addition of organic materials such as farm yard manure brings appreciable increase in TOC (Table 6) as compared with the treatments containing inorganic fertilizers alone. Total simulation error in terms of RMSE for Panjri ranged from 2.14 to 6.52% (Table 7). The simulation bias expressed by *M* as well as Student's *t* was found to be not significant for all the treatments (Table 7). The simulation correlation coefficient (*r*) ranged within 0. 78–0.99.

3.3. Performance of model and plant C input in southern black soil region

Teligi data showed that organic carbon added through external sources like cow dung slurry, paddy straw and *Gliricidia* (T6, T8 and T10) increased TOC (Table 6; Fig. 4). It was also observed that a regular application of NPK (T2, Table 6) marginally influenced TOC during the experimental period (1984–1995) (Fig. 5).

There was no noticeable increase in TOC content after addition of inorganic fertilizers only (Fig. 3). Addition of inorganic fertilizer in combination with organic (T6, T8 and T10) brings appreciable increase in TOC over years. Roth*C* registered an increase in TOC beyond experimental period when compared with control. Addition of organic materials such as cow dung slurry (CDS), paddy straw (PS), *Gliricidia* bring appreciable increase in TOC content (Table 6) as compared with the treatments containing inorganic fertilizers alone. The total simulation error in terms of RMSE for Teligi ranged from 1.45 to 13.74% (Table 7) which was in the similar range of those obtained in Sarol and comparatively smaller than the values obtained in Nabibagh. The simulation bias expressed by *M* as well as Student's *t* was found to be not significant for all the treatments (Table 7). The simulation correlation coefficient (*r*) ranged from 0.22 to 0.97. Interestingly control treatment (T1) indicates unbiased model output in spite of r showing non-significant value (0.22).

4. Discussion

For Sarol, addition of inorganic fertilizers alone increased TOC marginally while introduction of manure brought an increase in TOC (Table 6). Increase in TOC is controlled by nature and quality of clay in soils (Bhattacharyya et al., 2000). Relatively high clay content in these four spots (Table 2) influencing favoured moisture condition for organic matter decomposition in these soils (Vertisols) helped in increasing TOC when manures were added (Bhattacharyya et al., 2005) (Table 6). Earlier Coleman et al. (1997) found an increase in TOC with the regular application of NPK in temperate climate.

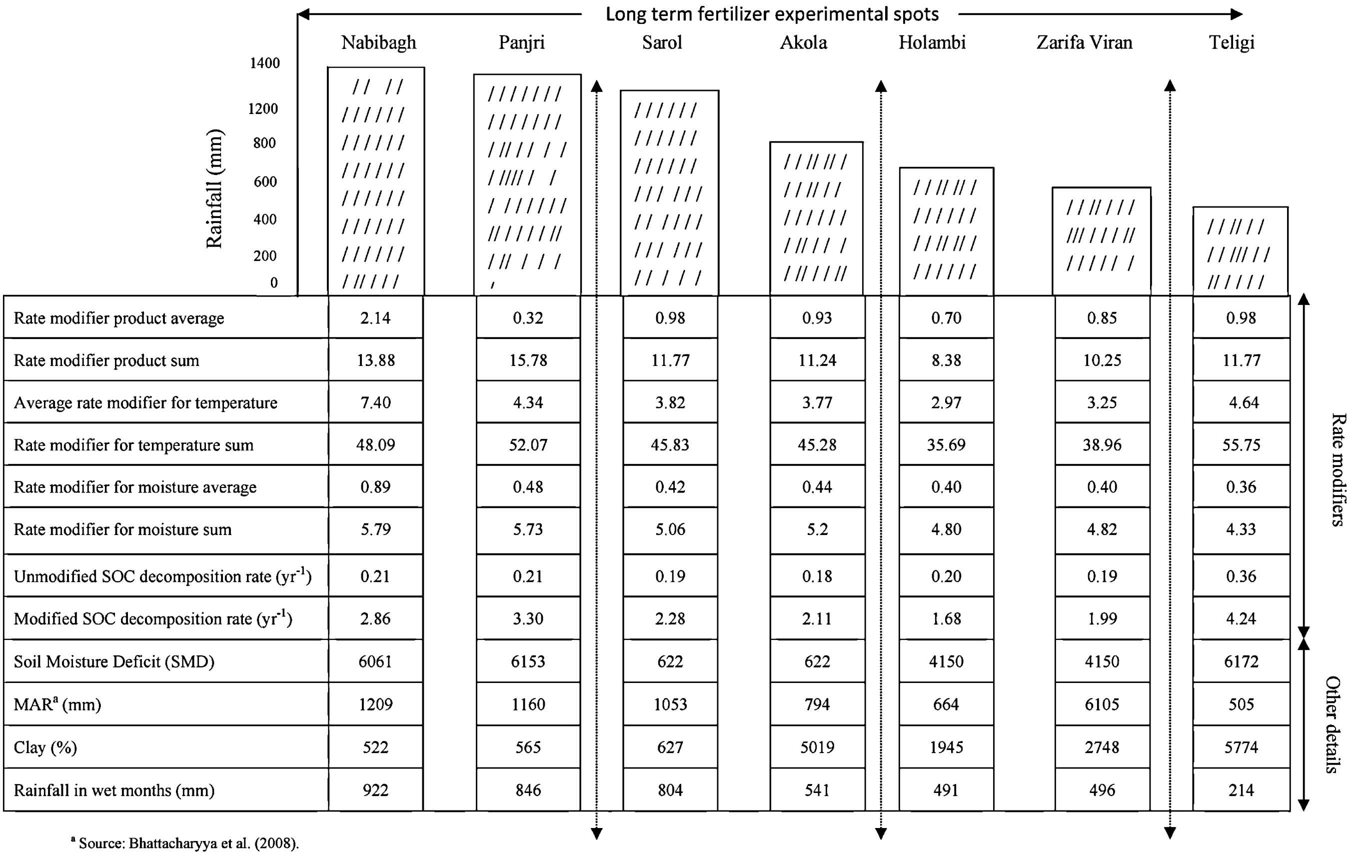
The relative effect of the application of manures for TOC increase in Teligi reported earlier was *Gliricidia* > PS > CDS (Bellaki et al., 1998). These authors stated that this could be attributed to addition of organic materials and also due to better root growth, more plant residue after harvest of the crop and indirect influence on the physical and chemical characteristics of soil. Modelled TOC values support the earlier observations (Bellaki et al., 1998) which is in line with the content of TOC in these amendments (42.0, 41.5 and 33.3% C for PS, *Gliricidia* and CDS, respectively).

Table 8
Various pools of C content of the soil under various LTFEs in control treatment.

Various pools of C content	On June 1860	On June 1983	On June 1988	DPM/RPM		
				1860	1983	1988
Sarol						
DPM	0.02	0.07	0.07	0.01	0.04	0.04
RPM	1.77	1.56	1.93			
BIO	0.15	0.16	0.21			
HUM	5.81	5.83	5.92			
IOM	0.70	0.70	0.70			
Various pools of C content	On June 1860	On June 2002	On June 2005	DPM/RPM		
				1860	2002	2005
Nabibagh						
DPM	0.05	0.15	0.15	0.01	0.05	0.08
RPM	3.17	2.68	1.80			
BIO	0.27	0.29	0.28			
HUM	10.22	10.26	10.33			
IOM	0.85	0.85	0.85			
Various pools of C content	On June 1860	On June 1986	On June 1997	DPM/RPM		
				1860	1986	1997
Panjri						
DPM	0.19	0.20	0.20	0.05	0.10	0.11
RPM	3.86	1.88	1.79			
BIO	0.42	0.31	0.29			
HUM	16.14	11.91	11.96			
IOM	1.25	1.25	1.25			
Various pools of C content	On June 1860	On June 1984	On June 1994	DPM/RPM		
				1860	1984	1994
Teligi						
DPM	0.04	0.05	0.14	0.03	0.05	0.07
RPM	1.09	1.99	1.82			
BIO	0.12	0.13	0.23			
HUM	4.81	4.82	8.28			
IOM	1.25	1.25	1.25			

Singh et al. (2004) earlier reported that organic carbon content in the surface soils in Nabibagh increased significantly with the repeated additions of farm yard manure/poultry manure/urban compost along with 50% NPK and 5 t FYM ha^{-1} to soybean and 100% NPK to wheat. The modelled TOC values followed this trend. Similar trend for TOC was observed in Panjri.

Table 8 gives the value of various pools of C content of the soils under various LTFEs in control treatment. At the end of the preliminary run to equilibrium on June, 1860 up to the time the model had run for 10,000 years using the various weather files (Sarol, Nabibagh, Panjri and Teligi), the C content showed variations in different LTFEs. We have tabulated the various pools on June during the beginning and at the end of the experimental period. It is interesting to observe that Roth*C* calculates relatively high inert organic matter at LTFE spots receiving more mean annual rainfall (MAR). The DPM/RPM ratio also followed similar trend with MAR with Sarol as an exception. This is due to low initial TOC content of Sarol (6 t ha^{-1}) as compaired to Panjri (15 t ha^{-1}), Nabibagh (12 t ha^{-1}) and Teligi (10 t ha^{-1}). Fig. 5 gives decomposition rate modifiers for moisture and temperature (and their sums), and modified and unmodified SOC decomposition rates at all modelled sites, calculated by Roth*C*.



	Nabibagh	Panjri	Sarol	Akola	Holambi	Zarifa Viran	Teligi
Rate modifier product average	2.14	0.32	0.98	0.93	0.70	0.85	0.98
Rate modifier product sum	13.88	15.78	11.77	11.24	8.38	10.25	11.77
Average rate modifier for temperature	7.40	4.34	3.82	3.77	2.97	3.25	4.64
Rate modifier for temperature sum	48.09	52.07	45.83	45.28	35.69	38.96	55.75
Rate modifier for moisture average	0.89	0.48	0.42	0.44	0.40	0.40	0.36
Rate modifier for moisture sum	5.79	5.73	5.06	5.2	4.80	4.82	4.33
Unmodified SOC decomposition rate (yr^{-1})	0.21	0.21	0.19	0.18	0.20	0.19	0.36
Modified SOC decomposition rate (yr^{-1})	2.86	3.30	2.28	2.11	1.68	1.99	4.24
Soil Moisture Deficit (SMD)	6061	6153	622	622	4150	4150	6172
MAR[a] (mm)	1209	1160	1053	794	664	6105	505
Clay (%)	522	565	627	5019	1945	2748	5774
Rainfall in wet months (mm)	922	846	804	541	491	496	214

[a] Source: Bhattacharyya et al. (2008).

Fig. 6. Schematic diagram showing the decomposition rate modifiers in different Long Term Fertilizer Experiments. The LTFE spots of Akola, Holambi and Zarifa Viran are shown for comparison to find the threshold limits for rainfall and not discussed in this paper.

A closer look at Fig. 6 indicates that the rate modifiers vary in different LTFE spots. It is noted that rate modifier for moisture sum gradually decreases from sub-humid moist to arid bioclimatic system with a clear distinction at Sarol, Akola and Zarifa Viran. Various other details of these sites vis-à-vis the rate modifiers indicate that rainfall during the wet months of nearly 850, 550 and 500 mm appear to be the three threshold limits in these five bioclimatic systems in deciding the rate modifier for moisture sum (b in RothC model, Coleman and Jenkinson, 1999). It means below the rainfall of this wet month the organic carbon turnover rate will be reduced causing less organic carbon storage in soils. While explaining inorganic carbon sequestration and its consequences to soil sodicity a threshold limit of 850 mm MAR was reported (Bhattacharyya et al., 2000, 2004) below which the soils become more calcareous,

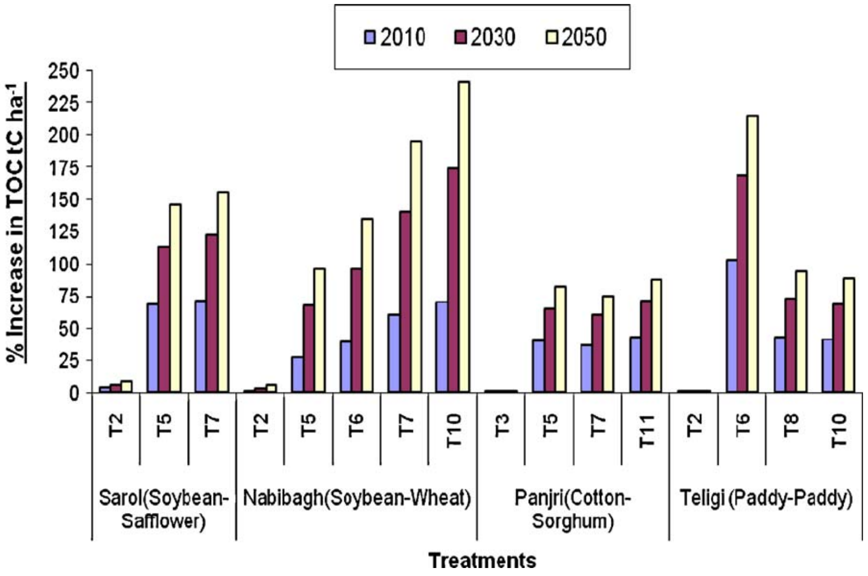


Fig. 7. Rate of change of modelled total organic carbon over control (T1) as influenced by management.

alkaline and sodic. Roth*C* model output can thus help to find out the threshold limits of climatic parameters to influence SOC decomposition and its content which can serve as a good indicator for soil quality and health.

While applying the model and evaluating its performance, many factors should be considered. Some of the important factors which affect the model error and performance are discussed below. The accuracy of measured data is mainly affected by sampling and analytical errors. The replicate values for any of the experimental sites under study were not available. Annual soil samples from these long-term experimental stations were usually analysed by different staff, and in some cases standard samples were not used in some earlier years because of the lack of the analytical facilities in local laboratories. Therefore, some extreme measured SOC values may have been the result of both sampling and analytical errors.

Roth*C* model showed that addition of only fertilizers shall maintain the TOC level in soils (Fig. 7, T2 in all the sites). To increase the level of organic carbon sequestration for the posterity, addition of organics along with fertilizers may be recommended. Recent findings on effects of organics on shrink–swell soils (Vertisols) indicate an increase in active pool of organic carbon (Chivhane and Bhattacharyya, 2010). Although such pools may not immediately influence crop yield but in due course of time crop yield and soil health will be bettered by such practice. Among organic manures, farm yard manure and wheat straw have, by far, the best combination for the maximum influence in organic carbon sequestration. The other options are cow dung slurry, urban compost and farm yard manure (Tables 1, 3–5).

5. Conclusion

The model was calibrated to simulate changes in soil organic carbon on typical black soils. It has been found that the model simulates the observation that inorganic fertilizers alone did not increase TOC, while the combination of inorganic and organic does so; in both the events however crop yields are increased.

Acknowledgements

This work forms a part of the Department of Science and Technology (DST), New Delhi sponsored project on "Predicting soil carbon changes under different cropping systems in soils of selected benchmark spots in different bioclimatic systems in India" as well as the Indian Council of Agricultural Research, New Delhi sponsored National Project on Climate Change entitled "Changes in soil C reserve as influenced by Different ecosystems and land use in India". The financial assistance is gratefully acknowledged. We are also grateful to the Director, NBSS & LUP, Nagpur, India for providing facilities to carry out this research.

References

Ardo, J., Olsson, L., 2003. Assessment of soil organic carbon in semi-arid Sudan using GIS and Century model. J. Arid Environ. 54, 633–651.

Arrouyas, D., Issabelle, V., Luckisin, J., 1995. Spatial analysis and modeling of top soil carbon storage in temperate forest humic loamy soil of France. Soil Sci. 169, 191–198.

Barde, N.K., Kalbande, A.R., Subramanyam, K.S., 1974. Report on the soil survey of medium agricultural research farm (UAS), Siruguppa, Bellary, Karnataka. Report No. 359, AISLUS, IARI, New Delhi, India.

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

Batjes, N.H., 2001. Options for increasing carbon sequestration in West African soils: an exploratory study with special focus on Senegal. Land Degrad. Dev. 12, 131–142.

Bellaki, M.A., Badnur, V.P., Setty, R.A., 1998. Effect of long-term integrated nutrient management on some important properties of a Vertisol. J. Indian Soc. Soil Sci. 46, 176–180.

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., Mandal, C., Telpande, B., 2008. Soil carbon storage capacity as a tool to prioritise areas for carbon sequestration. Curr. Sci. 95, 482–494.

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.

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., 2005. Landuse, clay mineral type and organic carbon content in two Mollisols-Alfisols-Vertisols catenary sequences of tropical India. Clay Res. 24, 105–122.

Chandran, P., Ray, S.K., Durge, S.L., Raja, P., Nimkar, A.M., Bhattacharyya, T., Pal, D.K., 2009. Scope of horticultural land use system in enhancing carbon sequestration in ferruginous soils of the semi-arid tropics. Curr. Sci. 97, 1039–1046.

Chivhane, S.P., Bhattacharyya, T., 2010. Effect of land use and bio-climatic system in organic carbon pool of shrink–swell soils in India. Agropedology 20, 145–156.

Coleman, K., Jenkinson, D.S., 1999. ROTHC-26.3. A Model for the Turnover of Carbon in Soil. Model Description and Windows Users' Guide. Nov.1999 Issue. Lawes Agricultural Trust, Harpenden, UK.

Coleman, K., Jenkinson, D.S., Crocker, G.J., Grace, K.J., Korschens, M., Poulton, P.R., Richter, D.D., 1997. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. Geoderma 81, 29–44.

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

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

Falloon, P., Smith, P., Szabo, J., Pasztor, L., 2002. Comparison of approaches for estimating carbon sequestration at the regional scale. Soil Use Manage. 18, 164–174.

Guo, L., Falloon, P., Coleman, K., Zhou, B., Li, Y., Lin, E., Zhang, F., 2006. Application of the RothC model to the results of long term experiments on typical upland soils in Northern China. Soil Use Manage. 23, 63–70.

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

Jenkinson, D.S., Coleman, K.C., 1994. Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. Eur. J. Soil Sci. 45, 167–174.

Jenkinson, D.S., Harkness, D.D., Vance, E.D., Adams, D.E., Harrison, A.F., 1992. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. Soil Biol. Biochem. 24, 295–308.

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.

Lal, S., Deshpande, S.B., Sehgal, J., 1994. Soil Series of India. NBSS Publication No.40. Nagpur, India: National Bureau of Soil Survey and Land Use Planning. 684.

Mandal, C., Mandal, D.K., Srinivas, C.V., Sehgal, J., Velayutham, M., 1999. Soil Climatic database for crop planning in India. NBSS Publ. 53, 1014. NBSS & LUP, ICAR, Nagpur, India.

Murthy, R.S., Bhattacharjee, J.C., Landey, R.J., Pofali, R.M., 1982. Distribution, characteristics, and classification of Vertisols. Trans. 12th Int. Cong. Soil Sci. 2, 3–22.

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

NBSS and LUP, 1994. Detailed Soil Survey of the farm of Indian Institute of Soil Science (ICAR), Nabibagh, Bhopal, Technical Report No.528. NBSS & LUP, ICAR, Nagpur, India.

Paustian, K., Levine, E., Post, W.M., Ryzhova, I.M., 1997. The use of models to integrate information and understanding of soil C at the regional scale. Geoderma 79, 227–260.

Rao, A.S., Shrivastava, S., 1998. Integrated nutrient management strategies for sustainable crop production in Central and Western India. In: Proceedings of National Workshop on Long Term Soil Fertility Management Through Integrated Plant Nutrient Supply. Indian Institute of Soil Science, Bhopal, India, pp. 89–100.

Saikh, H., Varadachari, C., Ghosh, K., 1998. Effect of deforestation and cultivation on soil CEC and content of exchangeable bases: a case study in Simlipal National Park. India. Plant Soil 204, 175–181.

Sharma, R.K., Gupta, R.K., 1993. Recent Advances in Dry Land Agriculture. Scientific Publisher, Jodhpur, pp. 411–428.

Singh, Muneshwar, Reddy, Sammi, K., Biswas, A.K., Raverkar, K.P., Mandal, K.G., Bandopadhyay, K.K., 2004. Long-term Evaluation of Integrated Plant Nutrient Supply Modules for Sustainable Productivity in a Vertisol. Annual Report 2003–04. Indian Institute of Soil Science, Bhopal, India, pp. 15–37.

Smith, J.U., Smith, P., Addiscott, W., 1996. Quantitative methods to evaluate and compare soil organic matter (SOM) models. In: Powlson, D.S., Smith, P., Smith, J.U. (Eds.), Evaluation of Soil Organic Carbon Matter Models Using Existing, Long-term Datasets. NATO ASI Series I vol. 38. Springer-Verlag, Berlin, pp. 181–200.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jemkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Muller, T., Parton, W.J., Thronley, J.H.M., Whitmore, A.P., 1997. Evaluation and comparison of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225.

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

Swarup, A., Wanjari, R.H., 2000. Three Decades of All India Coordinated Research Project Long Term Fertilizer Experiments to Study Change in Soil Quality, Crop Productivity and Sustainability. Indian Institute of Soil Science, Bhopal, India, p. 335.

Tamgadge, D.B., Gajbhiye, K.S., Velayutham, M., Kaushal., G.S., 1999. Soil series of Madhya Pradesh, NBSS Publ. No. 78, NBSS & LUP Nagpur, India.

Van Keulen, H., 2001. Tropical soil organic matter modelling: problems and prospects. Nutr. Cycling Agroecosyst. 61 (1/2), 33–39.

Venugopalan, M.V., Pundarikakshudu, R., 1999. Long term fertilizer experiment in cotton based cropping in rainfed vertisols. In: Proceedings of a National Workshop on Long-Term Soil Fertility Management through Integrated Plant Nutrient Supply. Indian Institute of Soil Science, Bhopal, India, p. 283.

Velayuthum, M., Pal, D.K., Bhattacharyya, T., 2000. Organic carbon stocks 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.

Walkley, A., Black, I.A., 1934. An estimation of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 37, 29–38.