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RESEARCH ARTICLE

Simulating change in soil organic carbon in two long term fertilizer experiments in India : with the Roth*C* model

T. Bhattacharyya* • D.K. Pal • S.K. Ray • P. Chandran • C. Mandal • B. Telpande • A.S. Deshmukh • P. Tiwary

Abstract Global importance of total organic carbon (TOC) in soil is due to its role in the global carbon cycle and, thus, the part it plays in influencing the atmospheric levels of greenhouse gases (GHGs). It is also of local importance as it determines ecosystem and agro-ecosystem function, influencing various soil parameters. The objective of the present study was to evaluate Roth*C* model (26.3) to estimate TOC changes under two long term fertilizer experimental (LTFE) sites representing humid (Mohanpur) and semi-arid (Akola) climate in India. Five treatments each at the LTFE sites of Mohanpur representing alluvial soils (Alfisol) of the Indo-Gangetic Plains (IGP) and of Akola dominated by black soils (Vertisols) in the Black Soil Region (BSR) were selected. Mohanpur site was modelled for 3 layers (0-13, 13-23, and 23-39 cm) while Akola for surface layer (0-15 cm) only. The root mean square error (RMSE), considered as modelling error, ranged from 3.34 to 17.85%, 6.87 to 14.22% and 6.66 to 24.34% in the 3 soil layers of Mohanpur site respectively. For Akola, RMSE ranges from 1.79 to 13.28. The simulation biases expressed by M (relative error) for all treatments at these sites were non-significant. In Mohanpur, observed trends in TOC show marginal increase in control (T1) and 100% NPK (T2) while the increase was nearly 17 to 35% when organic amendments were applied along with inorganics during 1999 to 2010. For the same period in Akola, control (T1), 50% NPK (T2), and 100% NPK (T4) recorded decrease in TOC while 26 to 29% increase was registered without inorganics and with the combination of inorganics and organics respectively. The calculation of modelled TOC stock to find out effect of global warming indicated that treating the entire soil pedon as a homogenous unit will overestimate effects of global warming in accelerating decomposition of soil carbon.

Keywords Global Warming, Roth*C*, Total Organic Carbon, Long Term Fertilizer Experiment.

Introduction

The main objective of the experiments in this study is to measure the effects of inorganic compounds containing nitrogen, phosphorus, potassium, sodium and magnesium elements on crop yields. The effects of these inorganic fertilizers alone and in various combinations were compared with those of farm yard manure (FYM). From 1957 several classical experiments were modified to evaluate the residual effects of the annually repeated dressings of different combinations of nutrients. Rothamsted experiment is one such classical example. These experiments continuously provide the most valuable information for changes in strategy and policy for continuous enhanced productivity without detrimental impact on environment.

In the beginning of the 20^{th} century, based on Rothamsted experiments, a series of long-term fertilizer experiments were established at different locations in India (Swarup and Wanjari, 2000). In these experiments the focus was mainly on production and development of a fertilizer requirement of cropping system and crop rotation. Long term experiments have been found to be a valuable resource to answer a few questions faced by the scientists. Collection of datasets by bringing together long term experiments offers the recognition of the benefits of these experiments; this has been more effective in terms of location, documentation and quality control of long term fertilizer experimental datasets. A significant contribution to address the climate change has come from model validation and scenario testing. To investigate changes in turnover of organic carbon in soils under various management practices the Roth*C* model has been used extensively (Coleman and Jenkinson, 1995; Falloon *et al.*, 2002; Jenkinson and Coleman, 2008).

Roth*C* model (26.3), basically concerned with soil organic matter turnover (Coleman *et al.*, 1997), finds its application in simulating as well as predicting changes in soil carbon stocks in varying climate and management conditions. Although there are efforts to test and simulate

Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur 440010, Maharashtra, India
Corresponding author Email ID: tapas11156@yahoo.com

soil organic carbon changes in tropical (Diels *et al.*, 2004; Shirato *et al.*, 2005; Kamoni *et al.*, 2007) and Mediterranean soils (Nieto *et al.*, 2010), very little effort has been made to evaluate Roth*C* in Indian conditions. An attempt has, therefore, been made to apply this model in two benchmark sites representing two long term fertilizer experiments (LTFE), one each in the Indo Gangetic Plains (IGP) and black soil regions (BSR) in India for its simulation, validation and its probable application in estimating soil organic carbon changes due to global warming.

Materials and Methods

Long Term Fertilizer Experiment (LTFE) Site at Mohanpur

The LTFE of Mohanpur (West Bengal, India) was carried out (8m*8m plot size) in the university farm, Bidhanchandra Krishi Vishwavidyalaya, West Bengal, India during 1986-2004 (Lat 22^{0}56$'$24.3$''$N, Long 89^{0}31$'$81$''$E). The rice (*Oryza sativa*) seedlings were transplanted in July. After the rice was harvested in the last week of October wheat (*Triticum aestivum*) was sown in the last week of November after the land was prepared by ploughing and harrowing. The plots were put under flooding with water, puddled with power tiller to a depth of 0.15 to 0.20 cm and then followed by laddering. The inorganic fertilizer doses, in the form of urea, single super phosphate and potash were applied in the treatments recommended by the state agricultural department (Majumder *et al.*, 2008; Table 1).

Three representative soil samples were collected from each plot from 0-20, 20-40 and 40-60 cm depth after 7-10 days (in the month of November, 2004) after harvesting rice (Majumder *et al.*, 2008). The experiment conducted for Mohanpur involved sampling at three depths such as 0-20, 20-40 and 40-60 (Mujamdar 2006). From the soil survey report the soil series description of Mohanpur shows the depths as 0-13, 13-23, 23-39, 39-57, 57-77, 77-88, 88-117 and 117-155 (Ray *et al.*, 2005). Since we know that RothC have a limitation for simulating organic carbon turnover at the subsurface, therefore, we decided to limit our exercise to three layers such as 0-13, 13-23 and 23-39 cm instead of 0-20, 20-40 and 40-60 cm. For validation purpose, however, the measured values of 0-20, 20-40 and 40-60 cm were used after converting SOC for the weighted mean average of 0-13, 13-23 and 23-39 cm.Total soil organic carbon determined by CHN analyzer (Majumder *et al.*, 2008) for all these layers were used as measured carbon as discussed later. This LTFE represents alluvial soils of the IGP. Mohanpur soil is a member of fine, mixed, hyperthermic Vertic Endoaqualfs (Ray *et al.*, 2005). These soils are formed in alluvium of nearly level old flood plain at an elevation of about 210 m above the mean sea level. The surface soil (0-20 cm) of the experimental site for all treatments had oxidisable (Walkely and Black, 1934) organic carbon of 8.8 g kg^{-1}, calcium carbonate equivalent 1.0 %, bulk density of 1.2 Mg m^{-3} and cation exchange capacity of 22.0 cmol (p$^+$) kg^{-1} (Majumder *et al.*, 2008). Rice and wheat crops were grown annually using power tiller and other management techniques including addition of fertilizers, farm yard manures, weeding, irrigation and plant protection measures (Mandal et al 2008). The experiment was laid out in a Randomized Block Design (RBD) with four replications showing various treatments. The 100% NPK dose was calculated on the basis of soil test value before the experiment was started. This dose (kg ha^{-1}) was 120:60:60 (N:P:K) for rice and 100:60:40 (N:P:K) for wheat. (Table 1) (Majumder, 2006; Majumder *et al.*, 2008). The climate is humid sub tropical with mean annual air temperature of 26.6 ^{0}C (mean annual maximum 31.6 ^{0}C, and mean annual minimum 21.7 ^{0}C) and mean annual rainfall of 1619 mm (Table 1). Actual mean monthly temperature (calculated from maximum and minimum monthly temperatures), and average rainfall for 50 years (1951 to 2000) were used for creating the weather files.

Long Term Fertilizer Experiment (LTFE) Site at Akola

A long term fertilizer experiment started in the year 1988 at Dr. Punjabrao Deshmukh Krishi Vidyapith, Akola (20^{0}57’04" N, 76^{0}57’05"E). The LTFE site of Akola represents a typical shrink-swell soil (Vertisol) of the BSR. The experiment was conducted with twelve treatments (Rawankar *et al.*, 2004) of which five were selected for the present study. Sorghum and wheat crops were used for this experiment.

The experiments were laid out (10m*10m plot size) in randomized block design (RBD) with four replications. The recommended (100% NPK) dose was calculated on the basis of soil test value before the experiment was started. This dose (kg ha^{-1}) was found to be 100:50:40 for sorghum and 120:60:60 for wheat. Full recommended (100 % NPK) dose was worked out as 100:50:40 for sorghum and 120:60:60 for wheat. FYM was thoroughly mixed with soil before sowing of sorghum. NPK was supplied through urea, single super phosphate and murate of potash, respectively to both the crops. Half the dose of N and full dose of P and K were applied at sowing and remaining half of N was top dressed (Table 1).

For the determination of total organic carbon the soil samples were collected in 1988 and 1997. Akola soils belong to fine, smectitic, hyperthermic Udic Haplusterts (Bhattacharji and Barde, 1974). These soils are clayey, slightly alkaline with organic carbon of 4.6 g kg^{-1}, CEC 41.6 cmol (p$^+$) kg^{-1}, calcium carbonate equivalent 5.7%, and bulk density ranging from 1.26 to 1.31 Mg m^{-3} at a depth of 0-0.15 m. Akola site represents semi- arid tropical climate with

Table 1 Details of Long Term Fertilizer Experiments at Mohanpur and Akola

Treatments	Crop	Inorganic fertilizer applied (kg ha^{-1})			Organic manure applied (t ha^{-1})	C in organic manure (t ha^{-1})	Crop yield (t ha^{-1})	
		N[a]	P[b]	K[c]			Rice	Wheat
Mohanpur [d] (Alluvial soils : fine, mixed, hyperthermic Vertic Endoaqualf)								
T1 = Control	Rice	Plots did not receive			0	0	1.301	0.80
	Wheat	NPK fertilizers and FYM						
	Fallow							
T2 = 100% NPK	Rice	120	60	60	0	0	3.234	2.57
(recommended)	Wheat	100	60	40				
	Fallow							
T3 = 100% NPK + FYM	Rice	120	60	60	7.5	2.490	3.611	2.88
	Wheat	100	60	40				
	Fallow							
T4 = 100% NPK +	Rice	120	60	60	10.0	0	3.433	2.90
Paddy Straw	Wheat	100	60	40				
	Fallow							
T5 = 100% NPK +	Rice	120	60	60	8.0	0	3.312	2.79
Green Manure	Wheat	100	60	40				
	Fallow							
Akola [e] (Shrink-Swell soils: fine, smectitic, hyperthermic Udic Haplustert)								
							Sorghum	Wheat
T1 = Control	Sorghum	Plots did not receive			0	0	0.71	1.105
	Wheat	NPK fertilizers and FYM						
T2 = 50% NPK	Sorghum	50	25	20	0	0	2.623	2.208
	Wheat	60	30	30				
T4 = 100% NPK	Sorghum	100	50	40	0	0	3.224	3.080
	Wheat	120	60	60				
T13 = 100% NPK + FYM	Sorghum	100	50	40	10.0	1.875	3.675	3.453
	Wheat	120	60	60				
T14 = Only FYM	Sorghum	0	0	0	10.0	1.875	1.934	1.876
	Wheat	0	0	0				

[a] N= Urea; [b] P= SSP (Single Super Phosphate); [c] K= MOP (Muriate of Potash); [d] MAR: 1619 mm; Tmax: 31.6 ^{0}C; Tmin: 21.7 ^{0}C; Clay: 32.8% for 0-13 cm, 30.9% for 13-23 cm and 39.2% for 23-39 cm soil depth; [e] MAR: 793 mm; Tmax: 34.5 ^{0}C; Tmin: 19.7 ^{0}C; Clay: 50.0% for 0-15 cm soil depth

mean annual maximum air temperature of 34.5 ^{0}C and mean annual minimum temperature of 19.7 ^{0}C with mean annual rainfall of 793 mm (Table 1). Mean monthly temperature (calculated from maximum and minimum monthly temperatures) and average rainfall was used for 36 years (1971 to 2007) to develop the weather files.

Description, evaluation, parameterization and calibration of RothC (26.3) model

Roth*C* is a model for the turnover of organic carbon for top soils that allows for capturing the effects of soil type, temperature, moisture deficit and plant cover on the turnover process. In Roth*C* model soil organic carbon is split into four compartments 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 grasslands. These values differ depending on type of the vegetation. It uses a monthly time step to calculate total organic carbon (TOC) (t C ha^{-1}), microbial biomass carbon (t ha^{-1}) and ^{14}C (from which equivalent radiocarbon date can be calculated) on years to centuries time scale (Jenkinson and Coleman, 1994). It needs few inputs which 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. The data required to run the model are monthly rainfall (mm), monthly evapotranspiration, average monthly mean air temperature, clay content of the soil (%), DPM/RPM ratio, soil cover (bare/vegetated), monthly input of plant residues (t C ha^{-1}), monthly inputs of farm yard manure (t C ha^{-1}), and the depth of soil layer (cm) (Coleman and Jenkinson, 1999). The model was run to simulate total organic carbon (TOC) for surface as well as subsurface layers. For both the sites, evapotranspiration (ET) values were estimated from potential evapotranspiration (PET) data (Mandal *et al.*, 1999; Coleman and Jenkinson, 1999). Soil moisture deficit (SMD) was calculated for the first three horizons of Mohanpur and surface horizon of Akola sites. Using SMD data, weather files for surface layers were created (Coleman and Jenkinson, 1999). We created weather files also for the subsurface layers of Mohanpur site using the similar steps.

Predicting changes in TOC turnover in Roth*C* model depends on temperature and moisture termed as rate modifying factors. The meteorological datasets provide air temperatures which have been modified to soil temperature to develop the weathered files. In the northern Hemisphere the Roth*C* starts since January. In the humid tropical regions like India we have parameterized the model so that it starts with the onset of the monsoon in the month of June and July. Accordingly we made changes to suit the climate of the various LTFE reported in this article. Soils attain a steady-state (quasi-equilibrium, QE) after accumulation of dry matter as well as loss of TOC overtime. After each change in landuse system a period of constant management is required to reach a new QE stage. Thus the SOC is stabilized in a landscape to another QE, characteristics of that changed situations in terms of new landuse pattern, vegetation, and management practice. In a forest system, under natural vegetation, SOC values attain a QE in centuries (500-1000 years) (Dickson and Crocker 1953). After forest cuttings agricultural systems attain QE in 30-50 years (Arrouys et al, 1995; Batjes, 2001). For Indian soils agricultural systems have been reported a QE in 5-15 years (Saikh et al, 1998; Naitam and Bhattacharyya, 2004, Chandran et al, 2009). It indicates that Akola (1988-1997) and Mohanpur (1986-2004) study sites have attained the QE. Soil organic matter models allow use of land use and land management history while projecting soil organic carbon stock (Ardo and Olsson, 2003; Milne *et al.*, 2007). It is in view of this the present study aims at predicting soil organic carbon stocks beyond experimental period. To find out the projected TOC (beyond 2004 for Mohanpur and 1997 for Akola) we presumed same plant inputs, IOM and other parameters as used for the treatments during 1988-1997 and 1986-2004 for Mohanpur and Akola respectively. There are efforts to find out relation between global warming vis-à-vis modelled TOC stocks (Jones *et al.,* 2005; Jenkinson and Coleman, 2008). Generally to estimate such warming effect on organic C held in terrestrial soil, Roth*C* considers the top soil with varying depth as a single homogeneous layer. Jenkinson and Coleman (2008) compared their datasets generated through Roth PC-1 for soils both as multilayer and as a single homogeneous unit. They concluded that assumption of top soil as a single unit grossly overestimates the effect of global warming.

We used three layers of soil (0-13, 13-23, and 23-39 cm) and generated datasets for modelled TOC stock for Mohanpur site only. This was compared with TOC stock of the same site considering 0-39 cm as a single unit. We presumed a subsequent increase in mean annual temperature of 0.25 ^{0}C per decade over 100 years (1990 to 2090) and ran Roth*C.* 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 ($D^{14}C$), the equation derived by Falloon *et al.* (2002) was used (IOM = 0.049/ $SOC^{1.139}$) to estimate the size of the IOM 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 model performance was then 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 between predicted and measured values exploring the total simulation bias, (iv) t of M (t-test of M). The critical values of t test of M and the Student’s t-test values are at 95% level of confidence. A value of t of M, lower than the critical two-tailed 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).

Results and Discussion

Modelled versus measured data: Mohanpur LTFE

Organic carbon added through external sources like, FYM (T3, @7.5 t ha^{-1}), paddy straw (PS) (T4, @10 t ha^{-1}), and green manure (GM) (T5, @8 t ha^{-1}) increases TOC (Table 1; Figs.1-3). It was also observed that a regular application

Table 2 Plant inputs and other simulation parameters for two long term trials

	IOM	PI	TOC (measured)		TOC (modelled)	
			1986	2004	1986	2004
	t C ha^{-1}					
Mohanpur						
0-13 cm soil depth						
T1 Control	1.0074	0.1677	13.73	14.21	14.19	13.77
T2 (100 %NPK)	1.2128	0.1971	13.73	16.73	14.13	13.70
T3 (100%NPK+FYM)	1.6708	0.2603	13.73	24.18	16.15	22.72
T4 (100%NPK+PS)	3.5769	0.5037	13.73	21.79	17.40	21.91
T5 (100%NPK+GM)	2.8037	0.4078	13.73	23.18	17.44	23.54
13-23 cm soil depth						
T1 Control	0.7273	0.1404	10.56	8.80	9.47	9.38
T2 (100 %NPK)	0.9739	0.1809	10.56	11.50	9.54	9.62
T3 (100%NPK+FYM)	1.2586	0.2261	10.56	17.28	11.47	18.32
T4 (100%NPK+PS)	1.9127	0.3261	10.56	17.85	12.63	18.17
T5 (100%NPK+GM)	2.4037	0.3964	10.56	16.10	12.53	18.06
23-39 cm soil depth						
T1 Control	0.5844	0.1168	12.32	11.02	13.39	13.77
T2 (100 %NPK)	0.9739	0.1809	12.32	11.23	13.41	13.57
T3 (100%NPK+FYM)	1.0690	0.1974	12.32	12.85	13.03	13.62
T4 (100%NPK+PS)	1.0390	0.1925	12.32	12.88	13.06	13.43
T5 (100%NPK+GM)	0.9574	0.1793	12.32	12.74	13.10	13.77
Akola						
			1988	2000	1988	2000
0-15 cm soil depth						
T1 Control	0.7553	0.0667	11.05	11.02	11.00	10.74
T2 (50 %NPK)	0.8004	0.0769	11.05	11.31	11.00	10.75
T4 (100% NPK)	0.8685	0.0818	11.05	11.72	12.02	11.19
T13 (100%NPK+FYM)	0.9818	0.0865	11.05	17.22	12.02	17.40
T14 (Only FYM)	1.2210	0.1100	11.05	17.32	11.96	17.05

Note: (i) IOM: Inert Organic Matter; PI: Plant Input (Per month); TOC: Total Organic Carbon
(ii) The DPM/RPM ratio used was 1.44 for 1986 onwards, the usual value for agricultural crops, while previous to 1986 it was 0.67 used for unimproved grasslands in the IGP, India.
(iii) Since 1986, two crops (paddy-wheat) were grown, keeping the ground covered for ten months leaving April and May as fallow months.
(iv) We presumed the same IOM, Plant Inputs and other parameters as used for the treatments during 1986-2004 to find out the projected TOC.

of NPK (Table 1) marginally increased TOC during the experimental period (1986-2004). A plant input of 2.6 t C ha^{-1} yr^{-1} for the treatments with NPK and 1.4 t C ha^{-1} yr^{-1} without NPK indicates an increase of plant carbon in the surface horizon (Figs. 1-3; Table 2). Earlier Coleman *et al.* (1997) found an increase of plant input 2.6 t C ha^{-1} in NPK and 2.1 t C ha^{-1} yr^{-1} in control in temperate climate.

Models for the turnover of subsoil carbon usually consider the downward movement of carbon and its subsequent stability in the subsurface horizons. Accordingly some models presume decrease in organic matter decomposition down the depth (Coleman *et al.*, 1997). A few reported the influence of hydroxides in clay to protect subsoil carbon (Masiello *et al.*, 2004). Recently Roth*C* (26.3) has been extended to include carbon at subsurface soils after introducing some modification to make a new model called RothPC-1 (Jenkinson and Coleman, 2008). We have however used Roth*C* to evaluate data for subsurface horizons with three soil depth intervals (Majumder, 2006). The second horizon (13-23 cm) of Mohanpur indicated almost similar

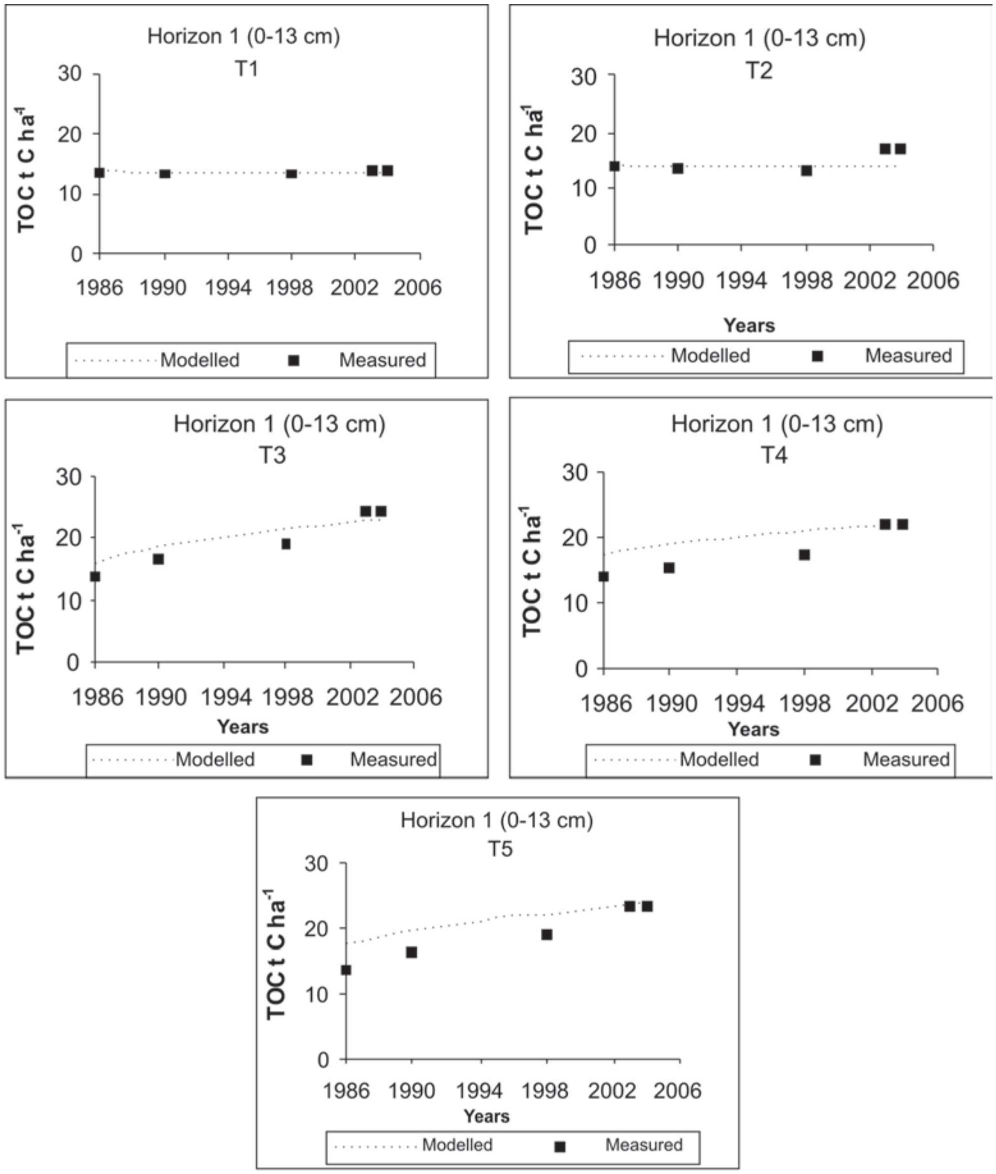

Figure 1 Modelled organic carbon contents of the first horizon (0-13 cm) of soils from five treatments on the LTFE site of Mohanpur

trend as observed in surface horizon (0-13 cm) (Figures.1-2; Table 2). In the third horizon (23-39 cm), T1 (control) produced higher SOC than T2 (100% NPK) (Fig.3; Table 2). Besides, we presumed contribution of FYM, paddy straw and green manure was nil since the external inputs for organic matter were generally limited to a depth of 20 cm (Jenkinson and Coleman, 2008). This is the reason why the model produces low SOC in the third layer as compared to first two horizons in treatments 3, 4 and 5. The rapid increase in soil organic carbon during the experimental period (1986-2004) is found in treatments 4 and 5 due to the addition of paddy straw and green manure. Addition of only FYM brought increase in SOC to a less extent.

Roth*C* model simulated the measured TOC at Mohanpur long term fertilizer trial (Fig 1-3; Table 2). The model errors (RMSE) were more than standard deviation (SD) in control (T1) and 100% NPK (T2) in all the three layers of Mohanpur and the surface layer of Akola sites (Table 3). It indicates that the model is not capturing the real scenarios in these treatments. However a closer look at the other statistical parameters viz. correlation coefficient (r), mean of errors, t value of M and Students' t test values indicate that the model can simulate the TOC well in T1 and T2 for the first layer of Mohanpur (0-13 cm) and Akola site (0-15 cm). For the remaining treatments in all the three layers of Mohanpur and surface layer of Akola, the model performance is

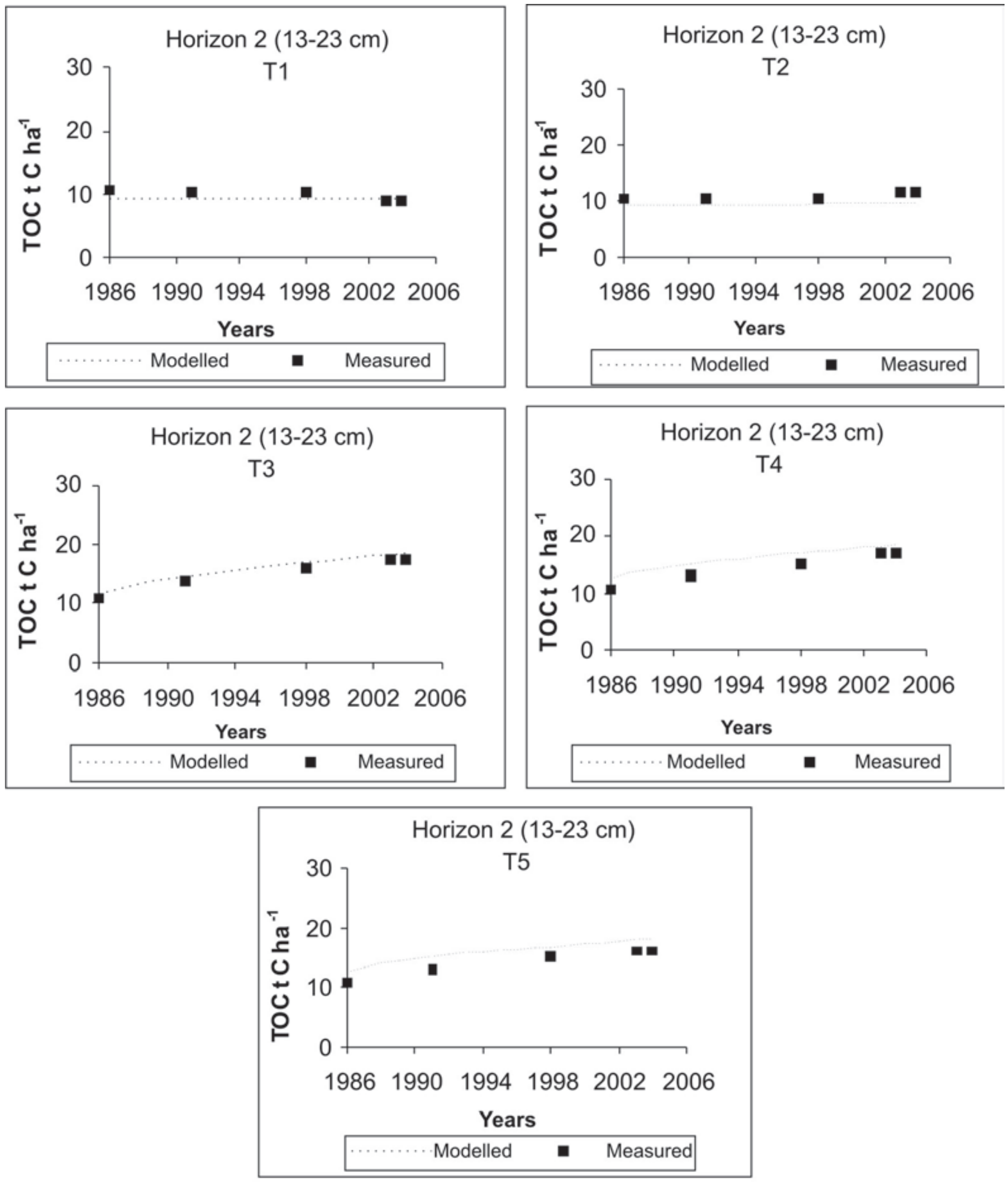

Figure 2 Modelled organic carbon contents of the second horizon (13-23 cm) of soils from five treatments on the LTFE site of Mohanpur

satisfactory since model errors (RMSE) were less than SD. The other statistical parameters also support this connotation (Table 3).

Plant C input in soils is governed by below-ground biomass, which is again determined by the crop production. The average grain yield of the five treatments during the experimental period is shown in table 1. Yield of rice and wheat was stable at treatment 3 (100%NPK+FYM) but the increase in TOC in treatments 4 and 5 was mainly because of application of additional carbon through paddy straw and green manure and that such external application of manure has increased TOC without influencing crop yield (Tables 1 and 6). The estimated plant C input rates (0-13 cm) were 1.458 t C ha^{-1} yr^{-1} and 2.5836 t C ha^{-1} yr^{-1} for winter wheat (rotation with paddy) for control and NPK treatments respectively. These values are different than those obtained for unmanured and NPK plots in temperate climate (2.1 and 2.6 t C $ha^{-1}yr^{-1}$in Bad Lauchstadt experiment) (Jenkinson *et al.*, 1992; Coleman *et al.*, 1997) and the cold Northern China (1.08 and 1.80 t C $ha^{-1}yr^{-1}$) (Guo *et al.*, 2006). Roth*C* predicted almost similar values in TOC beyond 2004 when compared with the control in Mohanpur (Table 4). Addition of organics further aided in increasing TOC. Taking 1990 as the base year, relative increase in TOC was high in treatment 4 (NPK+PS) followed by treatment 5 (NPK+GM) and treatment 3 (NPK+FYM). It is interesting to note that

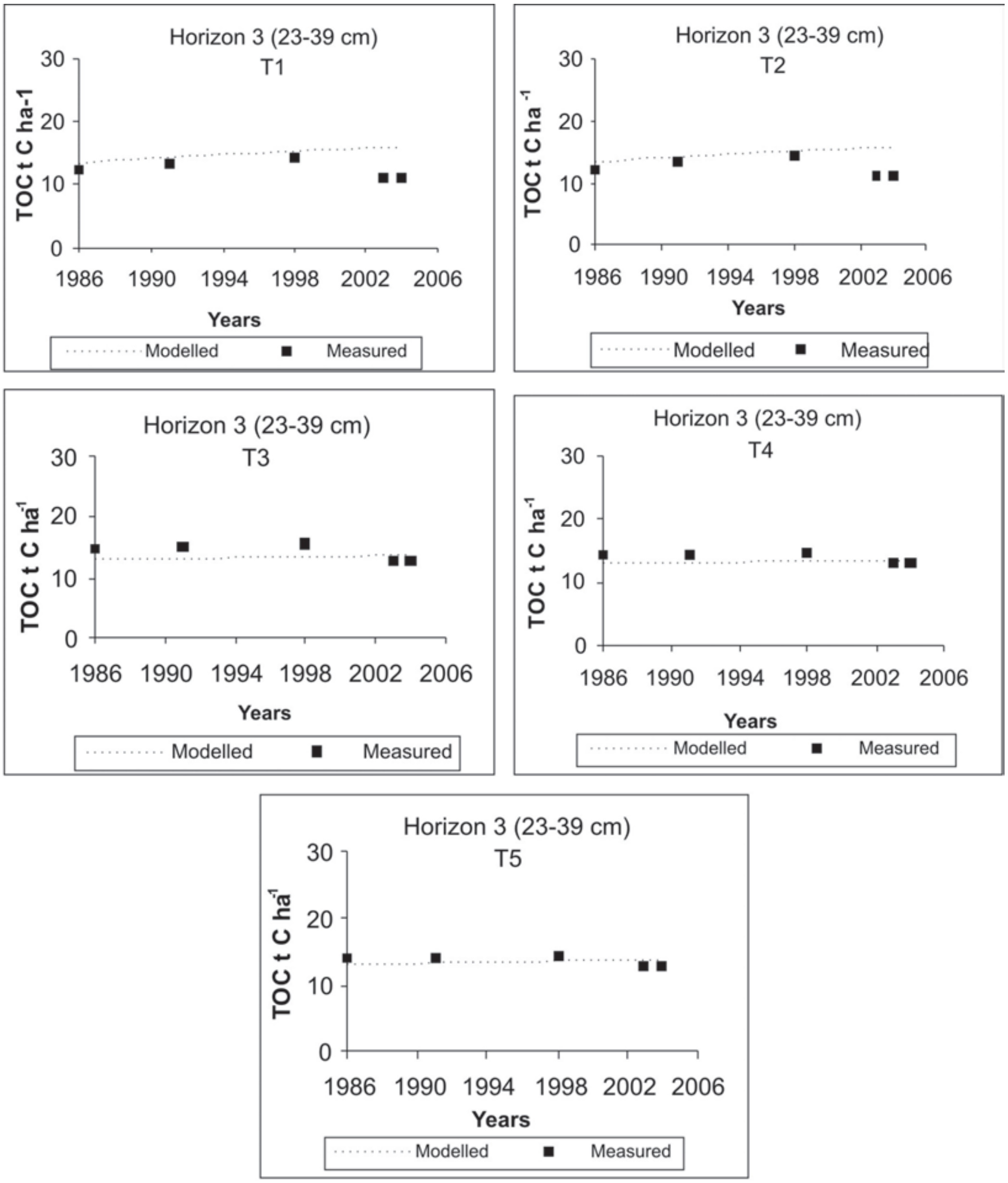

Figure 3 Modelled organic carbon contents of the third horizon (23-39 cm) of soils from five treatments on LTFE site of Mohanpur

increase in TOC content is more in the plots receiving both inorganic and organic in the first two layers (0-13, 13-23 cm). This trend is not observed in 3rd layer (23-39 cm). It shows that addition of organic matter in Mohanpur soils influences soil C turnover up to a depth of 23 cm (Table 4).

Modelled versus measured data: Akola LTFE

Akola site was modelled for the surface horizon (0-15 cm). Akola LTFE data indicated that TOC marginally increased when organic carbon is externally added through inorganic fertilizers (T2, T4, T13, T14) when compared with control (T1),with regular application of NPK increases TOC (T2, Fig 4; Table 2).

The total simulation errors in terms of RMSE in Akola range from 3.26 to 13.28 % (Table 3) in Mohanpur. 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 two-tailed t-value (Table 3). The simulation correlation coefficient (r) ranged between 0.912 to 0.994.

The average grain yield of four treatments at Akola site during the experimental period is shown in table 1. A close look at yield data (Table 1) and TOC (Table 4) indicate that

Table 3 Model errors and simulation bias for two experimental sites

Treatments	RMSE[a] (tCha^{-1})	r[b]	M	t value of M[c]	Student's t[d]	significance of bias (yes/no)[e]	significance of bias (yes/no)[f]	SD[g]
		Simulation error				Simulation bias		
Mohanpur (0-13 cm)								
T1 Control	0.46 (3.34)	0.75	-0.10	0.10	0.47	no	no	2.89
T2 (100% NPK)	1.94 (13.13)	0.80	0.96	0.06	1.19	no	no	10.89
T3 100%NPK+FYM)	2.06 (10.53)	0.97	-0.93	0.05	0.38	no	no	21.13
T4 (100%NPK+PS)	3.23 (17.85)	0.97	-2.74	0.07	1.47	no	no	17.98
T5 (100%NPK+GM)	2.89 (15.17)	0.98	-2.42	0.08	1.08	no	no	19.58
Mohanpur (13-23 cm)								
T1 Control	0.92 (9.42)	0.85	0.42	0.11	1.03	no	no	8.33
T2 (100% NPK)	1.43 (13.07)	0.84	1.36	0.20	5.70	no	yes	4.33
T3 (100%NPK+FYM)	1.03 (6.87)	0.97	-1.01	0.28	0.54	no	no	17.22
T4 (100%NPK+PS)	1.78 (12.27)	0.99	-1.73	0.15	1.05	no	no	17.14
T5 (100%NPK+GM)	2.01 (14.22)	0.98	-2.00	0.15	1.32	no	no	15.08
Mohanpur (23-39 cm)								
T1 Control	2.07 (15.96)	0.46	-1.98	0.11	3.28	no	yes	5.64
T2 (100% NPK)	3.04 (24.34)	0.41	-2.56	0.07	3.25	no	yes	9.77
T3 (100%NPK+FYM)	1.59 (11.13)	0.75	0.58	0.07	1.44	no	no	8.08
T4 (100%NPK+PS)	1.09 (7.93)	0.76	0.34	0.11	1.41	no	no	5.78
T5 (100%NPK+GM)	0.91 (6.66)	0.68	0.06	0.01	0.15	no	no	5.23
Akola (0-15cm)								
Control	0.39 (1.79)	0.91	0.15	0.98	1.85	no	no	1.08
T2 (50% NPK)	0.36 (3.26)	0.92	0.25	0.47	2.20	no	no	1.90
T4 (100% NPK)	1.34 (13.28)	0.90	-1.28	0.21	3.57	no	yes	6.42
T13 (100%NPK+FYM)	0.95 (8.01)	0.93	-0.95	0.31	2.96	no	yes	3.91
T14 (Only FYM)	0.91 (6.08)	0.97	-0.18	0.05	0.11	no	no	17.32

[a]Parentheses indicate % error value from mean measured value; [b]Critical values are at 5% level of significance; [c]Critical t value (at two tailed) is 2.31; [e]On the basis of t of M; [f]On the basis of Student's 't'; [g]Standard Deviation (SD) of measured values

$$^{d}\text{Student's 't'} = \frac{\textit{Mean of measured value} - \textit{Mean of modelled value}}{\sqrt{\textit{Variance of observed value} + \textit{Variations of modelled value/n}}}$$

application of only inorganic fertilizer (T2) does not increase TOC but increases crop yield; application of inorganic fertilizer in combination with organic (T13) brings increase in TOC as well as crop yield whereas, application of organic manure alone (T14) brings increase in TOC without significant increase in crop yield. Estimated plant carbon input rates (0-15 cm) were 0.7152 t C ha^{-1} yr^{-1} for control and 0.87 t C ha^{-1} yr^{-1} in plots receiving 50% NPK. These values are 0.816 and 0.708 t C ha^{-1} yr^{-1} for NPK+FYM and only FYM plots. In Akola addition of inorganic fertilizers alone does not increase TOC content over years (Table 4). Addition of inorganic fertilizer in combination with organic (T13) as well as only organics (T14) brings appreciable increase in TOC over years.

Effect of warming on modelled TOC stocks

Terrestrial Ecosystem model was used to find out equilibrium responses of soil carbon to climate change by Mcguire *et al.* (1995). The global process-based loss of SOC was reported to be 26.3 Pg assuming 1^{0}C warming. Their analysis indicated that the maximum loss of SOC/^{0}C warming is less than 2% of the terrestrial soil carbon stock. These authors suggested that soil moisture is useful to incorporate in the empirical models to arrive at better SOC responses. Later Shibu *et al.* (2006) reported that the soil in submerged paddy fields should be divided into two zones, such as, a flooded top layer 0-15 cm (the partially or fully reduced soil horizons) and a completely reduced subsurface horizon.

Table 4 TOC stock changes in different treatments over simulation years in Mohanpur and Akola (t C ha^{-1})

Soil depth (cm)	1990	2010	2030	2050
		Mohanpur		
		T1 (Control-no fertilizer, no organics)		
0-13	13.84	13.89 (1)[a]	14.02 (1)	14.10 (2)
13-23	9.31	9.20 (-1)	9.02 (-3)	8.93 (-4)
23-39	14.16	13.98 (-1)	13.63 (-4)	13.22 (-7)
		T2 (NPK)		
0-13	13.78	13.64 (-1)	13.55 (-2)	13.50 (-2)
13-23	9.44	9.70 (3)	9.86 (4)	9.95 (5)
23-39	14.18	14.66 (3)	14.26 (1)	13.97 (-1)
		T3 (NPK+FYM)		
0-13	18.61	21.83 (17)	21.92 (18)	22.02 (18)
13-23	14.07	20.40 (45)	24.34 (73)	26.56 (89)
23-39	13.14	13.29 (1)	13.09 (0)	12.99 (-1)
		T4 (NPK+PS)		
0-13	19.03	25.79 (35)	31.03 (64)	34.52 (81)
13-23	15.06	20.85 (38)	25.23 (67)	27.60 (83)
23-39	13.04	13.31 (2)	13.10 (0)	13.03 (0)
		T5 (NPK+GM)		
0-13	19.71	25.65 (30)	29.42 (49)	31.65 (61)
13-23	14.96	21.07 (41)	25.19 (68)	27.42 (83)
23-39	13.25	13.60 (3)	13.58 (3)	13.55 (3)
		Akola		
		T1 (Control)		
0-15	11.39	11.12 (-3)	11.10 (-4)	11.08 (-4)
		T2 (50%NPK)		
0-15	11.39	11.12 (-2)	11.10 (-3)	11.08 (-3)
		T4 (100%NPK)		
0-15	11.69	10.53 (-10)	10.05 (-14)	9.70(-17)
		T13 (100%NPK+FYM)		
0-15	12.27	15.94 (29)	18.21 (81)	19.89 (104)
		T14(Only FYM)		
0-15	13.25	16.10 (26)	17.57 (72)	18.69 (92)

[a]Figures in the parentheses indicate percentage changes compared to 1990

These authors found that treating soil as a uniform layer (for eg. Century model) makes it less suitable than those (such DNDC model) which treat soil as 10 layers with each layers showing 5 cm of thickness. Realization of the usefulness of multi-layered soil carbon model faces a challenge for the modellers since most of the experimental studies rarely contain reliable time-series data of SOC in the long term fertilizer experimental trials (Shibu *et al.*, 2006; Milne *et al*., 2008).

Keeping this in view we attempted to use Roth*C* model to find out how a single layer carbon model responds to warming. To find out the difference of model performance assuming Mohanpur soil as a single layer (0-39 cm) and also as a combination of 3 layers (0-13, 13-23 and 23-39 cm), we ran the model for 10,000 years under the climatic conditions in the Mohanpur LTFE site to find out the equilibrium carbon content in 1990 (Fig.5). TOC held within top 39 cm is found to decrease by 7.35 per cent in single layer when compared to a fall of 7.24 per cent when the same soil was modelled dividing it into three layers. Treating soil as different layers project actual effects of global warming in accelerating decomposition of soil C and the resultant release of CO_2 from soil organic matter. Assuming TOC stock of treatment 1 (control) as base, the data showed that application of NPK fertilizers alone and in combination with organic amendments could bring sizeable increase in TOC stock. The effects of paddy straw (T4) and green manuring (T5) appear very high in increasing TOC stock (Fig.6). This shows the role of organic amendments to mitigate the effect of accelerated rate of soil organic C decomposition and thereby controlling the resultant release of CO_2 from soil to atmosphere.

There are two issues which emerged from this exercise as mentioned below:

- Effect of warming on SOC loss will be buffered with the increase in depth of soil. In other words deep to very deep soils should be able to withstand the bad effect of global warming and therefore soil conservation should be a recommended practice with special reference to humid tropical climate to conserve soil organic carbon.
- Soil clays act as an excellent binding agent to cement organic matter (humic acid) in presence of polyvalent cations (Vardachari *et al.*, 1991; Bhattacharyya and Ghosh, 1994). More recently it has been shown that organic carbon sequestration is controlled by the minerals to the tune of nearly 78 %. This fact assumes importance since it shows the influence of soil substrate in building up organic carbon in soil (Bhattacharyya and Pal, 2003). Application of regular dose of manures can act as a buffer to mitigate the effect of warming due to climate change. In the present example we found that paddy straw (PS) acts as the best among the sources of manures as shown in figure 6.

General Discussion

It has been observed that both the quantity and quality of clay has an immense effect in binding organic matter as clay-organic complexes. It may be mentioned that Mohanpur has clay percentage of 32.8 (mostly micacious) while Akola has 52.3% (mostly smectitic). It is well known that smectite

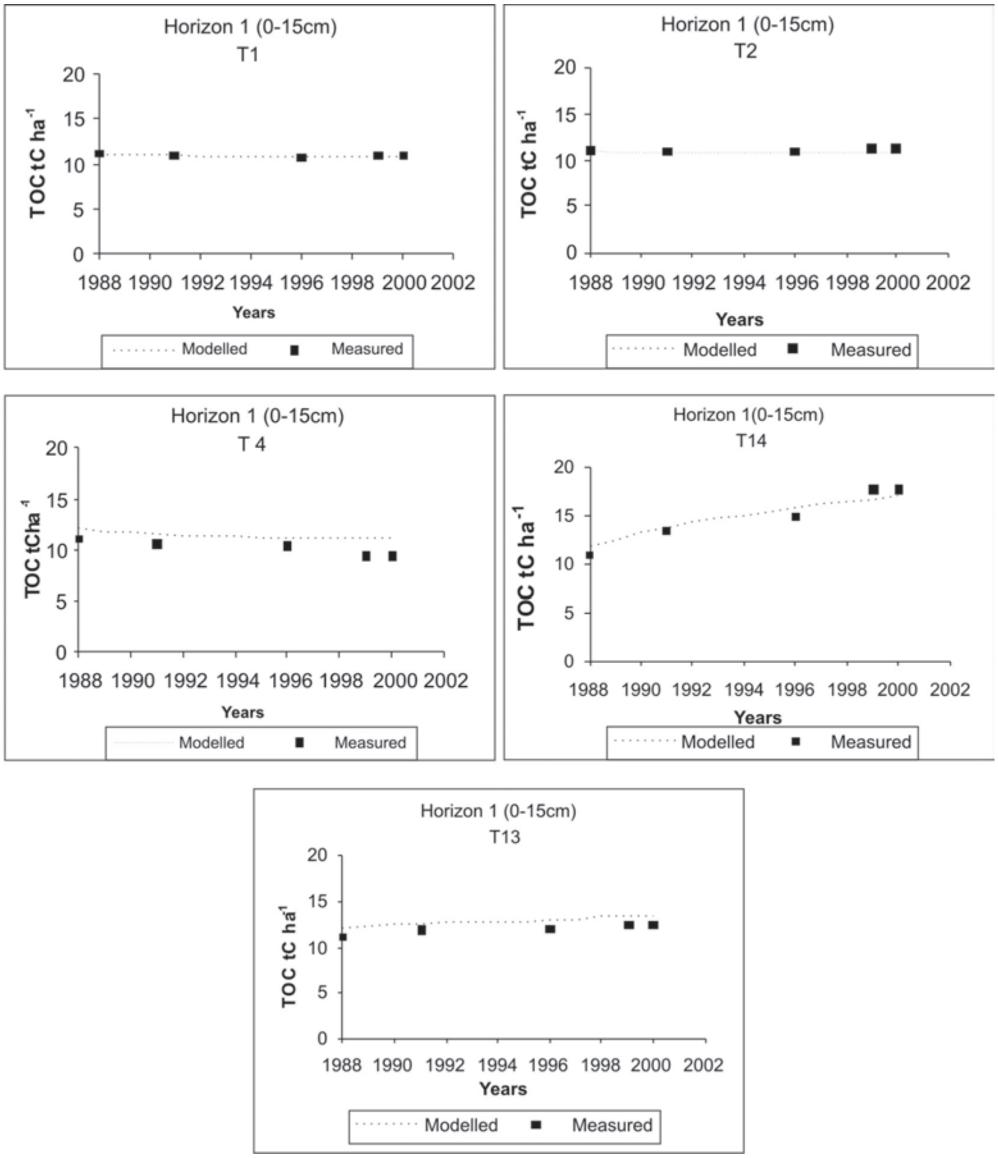

Figure 4 Modelled organic carbon contents of the surface horizon (0-15 cm) of soils from five treatments on the LTFE site of Akola

clay binds organic matter more tenaciously than micacious clay due to higher surface change density (Bhattacharyya *et al.*, 2000). In Akola (T13) the relative increase of TOC is 104% for 0-15 cm depth during 2050 indicating influence of substrate quality and quantity in sequestrating organic C in soils. The corresponding value for Mohanpur (T3) is 18%.

In Mohanpur the model was run for the first three horizons with varying depth intervals (Table 4). Change in TOC is relatively high (5 to 6%) in treatment 1 in the surface layer (0-13 cm). The increase in TOC continues in NPK treated plots (treatment 2) and also in other plots receiving manures (T 3, 4 and 5). The relative effect of the application of manures for TOC building reported earlier was FYM > PS > GM (Majumder *et al.*, 2008). These authors showed that C applied by FYM was low in resisting C decomposition as compared to GM. They found higher content of lignin and polyphenol in FYM (than PS and GM) to reduce the ease of decomposition of C. However Roth*C* derived TOC values follow the trend as PS > GM > FYM which is in line with the content of TOC in these amendments (42.0, 41.5, and 33.3% C for PS, GM and FYM respectively; Majumder, 2006). Such increase in TOC gradually slows down in the subsurface horizons due to low decomposition rate.

Evaluation of the Roth*C* model using the Mohanpur and Akola LTFE provides the model performance of two contrasting sites in terms of soils and climate (Fig. 4; Tables 2 and 3). Akola LTFE represents very clayey cracking soils (Vertisols) of the Black Soil Region (BSR) in the dry climate

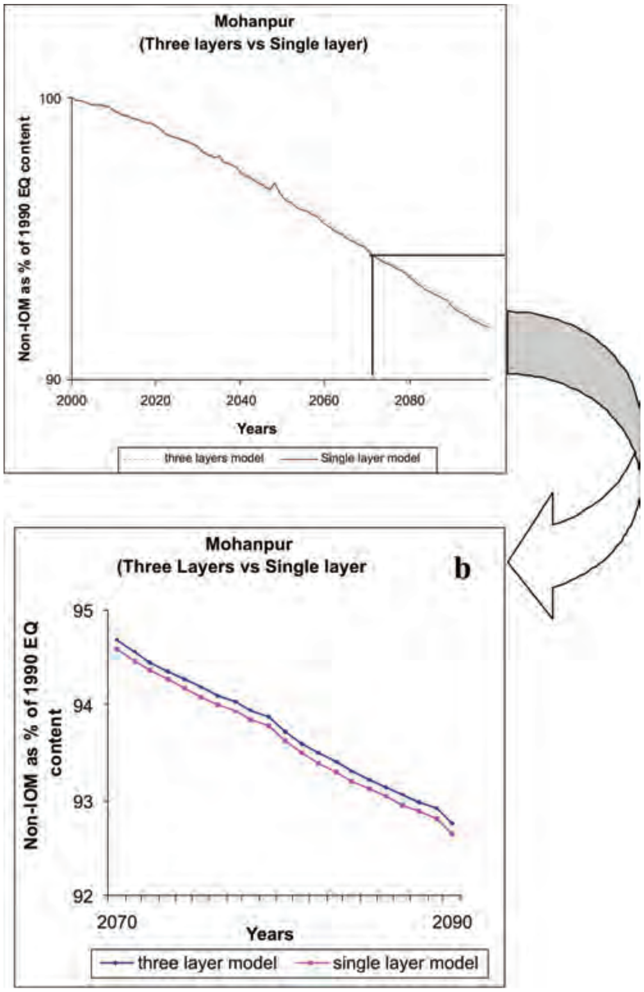

Figure 5 (a) Modelled organic carbon stocks in Mohanpur site subjected to an increase of 2.5 ^{0}C during 1990 to 2090. We considered two situations: 0-39 cm depth as a single layer and this depth is divided into three layers (0-13, 13-23 and 23-39 cm). Roth*C* was run for 10000 years to make 1990 as the equilibrium year using weather data of 1990; the mean annual temperature was then increased in decadal steps by 0.25 ^{0}C. We assumed the soil carbon without any IOM. The clay contents of the three layers were 32.80, 30.90 and 39.20 per cent; for the single layer this value was 34.30 per cent. The DPM: RPM ratio was 1.44 in all the cases. (b) Zoomed portion of figure 5a during 2070 to 2090.

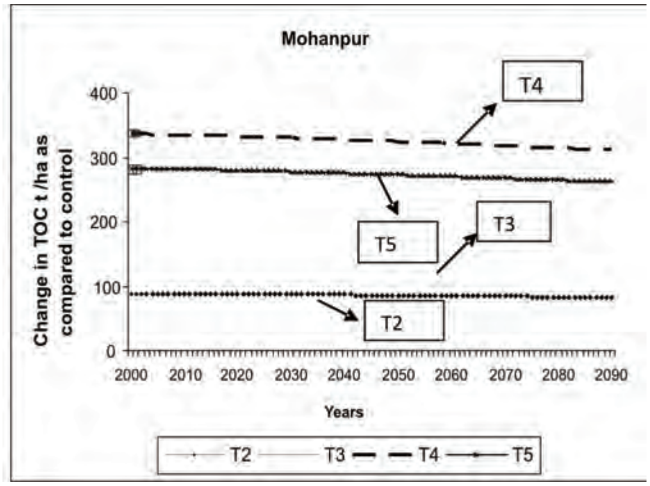

Figure 6 Modelled organic carbon stocks in Mohanpur site subjected to an increase of 2.5 ^{0}C during 1990 to 2090. Assuming treatment 1 (T1) as standard the percent fall in TOC content is more in treatment 2 (T2) (NPK) when compared to T3 (NPK + FYM), T4 (NPK + Paddy straw, PS) and T5 (NPK + Green manure, GM) which involves application of various organic amendments. This shows that increase in temperature due to global warming may be mitigated if soils are supplied with organic amendments along with NPK rather than putting NPK alone.

of the Deccan province; in contrast, the Mohanpur spot represents typical hydromorphic soils (Alfisols in aquic moisture regime) in the humid climate of eastern part of the Indo-Gangetic Plains (IGP) of India.

We have carried out the calculation of standard deviation (SD) of measured values for both the LTFE spots (Table 3). RMSE values are more than the SD of measured values in a few cases. If we observe table 3 more closely, we find that for Mohanpur (23-39 cm soil depth, T1 and T2) the higher RMSE values are justified because the correlation coefficient r is also low (0.41-0.46). In another example (Mohanpur 13-23 cm, T1 & T2), the lower values of r (0.84-0.85) perhaps justify more RMSE than the SD of measured values. In case of Akola (T4), more RMSE value indicates that perhaps 100% NPK in high clay containing soils is not being captured by RothC model. This has happened in spite of low t value of M indicating no biasness for model simulation (Table 3). We have also introduced Student's t test as an additional parameter to justify T2 (13-23cm), T1 and T2 (23-39cm) of Mohanpur and T4 (0-15cm) to justify the performance of model in terms of biases. We should consider many factors for application and evaluation of the performance of a model. The accuracy of measured values is controlled by sampling and analytical errors. In many cases the actual replicate values for the experimental sites were not available; staffs, sampling, analytical facilities vary in different experimental sites. Extreme measured values of TOC might have been the result of both sampling and analytical errors to influence the model performance.

For Akola, introduction of manure brings an increase in TOC over the treatment with only inorganic fertilizers by nearly 45-104% during 2050 (Table 4). It seems that addition of only inorganic fertilizers does not bring favourable environment in soils for the increase in TOC due to relatively high summer temperature (April, May and June) and mean maximum temperature (Tmax). Influence of low rainfall (793 mm) further decreases soil C (Table 1). Increase in TOC is controlled by nature and quality of clay in soils (Bhattacharyya *et al.*, 2000). Relatively high clay content

(50-56%, Table 1) which influences favourable moisture condition for organic matter decomposition in these soils (Vertisols) might have influenced in TOC built-up due to addition of organics in treatment 13 (100% NPK+FYM) when compared to treatment 4 (100% NPK) (Bhattacharyya *et al.*, 2005) (Table 4). Mohanpur site on the other hand can build up more TOC even when only inorganic fertilizers are added; the addition of organics in combination further increases soil organic carbon. The model predicted overall increase in TOC in the first two layers in Mohanpur. This increase is nearly 4 to 5% in the control and NPK plots, 17 to 89% in NPK+FYM plots and nearly 30 to 83% in plots receiving inorganic and organic combinations (PS & GM) when compared to modelled TOC values in 1990 (Table 4). In Akola the model predicts nearly 100 to 165% increase in TOC as compared to modelled TOC values in 1990. The control and 50% NPK plots in Akola do not show any predictaed change in TOC level till 2050 (Table 4).

Considering soil as a multilayer component the Roth*C* model captures the real scenario of global warming using TOC stocks as a parameter. The model also indicates the related consequences on accelerated organic C decomposition and release of CO_2 from soil to atmosphere. It seems the application of inorganic fertilizers in combination with organic amendments will arrest the accelerated soil organic C decomposition better than putting only inorganic fertilizers in the humid and semi-arid tropics.

Conclusions

Roth*C* follows the trends of experimental set up in terms of different management interventions in both the sites represented by humid and semi-arid climate. Despite usual soil carbon loss in semi-arid climate (Bhattacharyya *et al.*, 2000) addition of manure in Akola site (T13) causes greater increase in TOC when compared to Mohanpur (T3). It seems substrate (clay) quality and quantity can perhaps mitigate the effect of loss of TOC due to increased atmospheric temperature as it relates soil substrate and carbon sequestration (Six *et al.*, 2000; Bhattacharyya *et al.*, 2005). This is simulated well in Akola by Roth*C* model. Roth*C* output for multilayer model application indicates deeper soils to absorb the shock of global warming. This fact reaffirms conservation of deep and fertile soils against erosion.

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