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RESEARCH ARTICLE

Simulating soil organic carbon in high clay soils in India: DNDC model experience

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Abstract Performance of DNDC model was evaluated using a long term fertilizer experiment (LTFE) datasets at Akola, Maharashtra. The LTFE site represents a semi-arid climate with a mean annual rainfall of 793 mm. Sorghum and wheat crops were cultivated for nine years (1988-1997). The model was parameterized using crop data from black soil region and used to estimate the total organic carbon (TOC) under different nutrient management treatments. It underestimates the total organic carbon in all the treatments in two different ways such as for control (T1) and 50% NPK (T2), it performs less than the measured values in the beginning of the experiment, while for 100% NPK+FYM (T13) and only FYM (T14) treatments the underestimation is found at the end of the experiment. Modelled data analysis using statistical parameters showed 50% NPK treatment was satisfactory. An effort is made to find out the relative performance of three models namely Roth*C*, Century and DNDC using the same LTFE site. By far, Roth*C* model was found to be near to the values of measured TOC as compared to other.

Keywords LTFE, DNDC model, Organic Carbon

Introduction

Long-term experimental studies have shown that soil organic carbon (SOC) is highly sensitive to changes in land use. There is always a loss of SOC when a native ecosystem such as forest is converted to agricultural systems (Jenkinson and Rayner, 1977). But cultivation can also enhance SOC status of land through management interventions like reduced tillage and cover crops (Bhattacharyya *et al*., 2004). Incorporating crop residues or increasing manure application also increases SOC (Bhattacharyya *et al*., 2000). Rates of land use change are more in the tropics where the demand for land for multivariate users is increasing with the increase in population. Tropical agriculture currently feeds 70% of the world population (Lal and Sanchez, 1992). Much of this demand is being met by converting native ecosystems to cultivated or pastoral land, thereby releasing C from soils to the atmosphere (Batjes and Sombroek, 1997). Subsequent poor management of newly converted fragile land can then lead to further losses of SOC and eventual degradation of land. Despite the importance of tropical areas in terms of the percentage of global SOC stocks and the vulnerability of these stocks (Batjes, 1996), we still have relatively little information about soils in these regions and how they react to land use/land management practices.

With the increasing realization that the management of the agricultural land is an integral part of a global carbon market, the need for soil carbon models to simulate agricultural cropping rotations is well recognized. One such well-known model used to estimate carbon fluxes is Denitrification-Decomposition (DNDC) (Li, 2000). Plant growth plays an important role in regulating the soil water regime which could affect bio-geochemical processes within the soil profile. For the purpose of simulating the crop growth, a sub-model was build in DNDC. The DNDC model's capability for simulating soil carbon dynamics is a function of the inputs on detailed information on site characteristics, experimental management practices, and historical land use practices.

Although there are lots of studies to predict C in the soils of the Indo-Gangetic Plains very little work was carried out in the BSR. Earlier efforts on DNDC are confined to the work of Li *et al*. (1997, 2004) and Pathak *et al*. (2005). The

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Table 1 Selected biophysical and management datasets of long-term fertilizer trials in Akola, Maharashtra

Site characteristics	Akola[a]
Location	Akola, Maharashtra
Latitude/longitude	$20^0$57'04" N, $76^0$57'05" E
Site history	Deciduous and tropical woodland
Altitude (m)	247
Mean annual rainfall (mm)	793
Temperature (MAT)	26.5
Experiment start year (duration)	1988 (9)
Texture	Clay
Clay (%)	52.2
Silt (%)	21.7
Sand (%)	26.1
Bulk density (Mgm"3)	1.26[b]
pH	7.9
Organic C (%)	0.46 (1988)
Soil series (US classification)	Akola (Typic Haplusterts)

[a]Source for Akola: Ravankar *et al.* (1998, 2004).
[b]Measured value

present study was undertaken with an objective to simulate the SOC changes in a representative long term fertilizer experimental sites in the semi-arid tropics of India.

Materials and Methods

Experimental site

The Akola experiment was started in 1988 at Dr. Panjabrao Deshmukh Krishi Vidyapeth (University), Akola farm (Maharashtra, India) with sorghum–wheat cropping rotation (Ravankar *et al*., 1998, 2004). This experiment at Akola was later taken over as All India Coordinator Research Project (AICRP) on long term fertilizer experiment. The latest report of this LTFE indicates compilation of 24 cropping cycles by 2011-12 (QRT report, 2007-2012). As per the decision of QRT, various changes have been incorporated in the treatments since then. Since our purpose was not only to evaluate DNDC model but also to compare its performance with earlier published Roth*C* and Century model datasets (Bhattacharyya et al., 2007, 2010; 2011) we limited the estimated observations during 1988-1997 only. The site has deep black soils (Vertisols: Typic Haplusterts) under semi-aridic climate with MAR of 793 mm. Mean monthly maximum air temperature at this site ranges from 29.8 ^{o}C in January to 37.1 ^{o}C in June and minimum between 11.9 ^{o}C in January and 23.7 ^{o}C in July. The detailed site characteristic is presented in table 1. The experiment includes different combinations of inorganic and organic nutrient sources. For the present study, we have tried to simulate treatments 1, 2, 13 and 14 (Table 2). Treatment 1 is control (no inorganic and organics) while T2 was the plot with 50% NPK. Treatments 13 and 14 were chosen to compare the combined effect of inorganic and organic amendments (T13) and organic amendments alone (T14) on the turnover of total organic carbon.

Model Description

The Denitrification-Decomposition (DNDC) model (Li, 2000) is a generic model of C and N biogeochemistry in agricultural ecosystems. The model simulates C and N cycling in agro- ecosystems at a daily or sub daily time step. It consists of six interacting submodels: soil climate, plant growth, decomposition, nitrification, denitrification and fermentation (Li *et al*., 1997). In DNDC, SOC resides in 4 major pools: plant residue (i.e. litter), microbial biomass,

Table 2 Details of Long Term Fertilizer Experiments at 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]			Sorghum	Wheat
Akola[d] (Shrink-Swell soils: fine, smectitic, hyperthermic Udic Haplustert)								
T1 = Control	Sorghum	Plots did not receive NPK			0	0	0.71	1.105
	Wheat	fertilizers and FYM						
T2 = 50% NPK	Sorghum	50	25	20	0	0	2.623	2.208
	Wheat	60	30	30				
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: 793 mm; Tmax: 34.5 ^{0}C; Tmin: 19.7 ^{0}C; Clay: 52.2% for 0-15 cm soil depth

humads (or active humus), and passive humus. Each pool consists of 2 or 3 sub-pools with different specific decomposition rates. The soil climate submodel simulates soil temperature and moisture profiles based on soil physical properties, daily weather and plant water use. The plant growth submodel calculates daily water and N uptake by vegetation, root respiration, and plant growth and partitioning of biomass into grain, stalk and roots. The decomposition submodel simulates daily decomposition, nitrification, ammonia volatilization and CO_2 production by soil microbes. The submodel calculates turnover rates of soil organic matter at a daily time step (Li *et al*., 1994). The nitrification submodel tracks growth of nitrifiers and turnover of ammonium to nitrate. The denitrification submodel operates at an hourly time step to simulate denitrification and the production of nitric oxide (NO), N_2O, and dinitrogen (N_2). The fermentation submodel simulates methane (CH_4) production and oxidation under anaerobic conditions. The DNDC model simulates CH_4 and N_2O production/consumption through a kinetic scheme "anaerobic balloon" (Li, 2000; Stange *et al*., 2000; Li *et al*., 2004). The size of the anaerobic balloon sitting in a soil layer is defined to be the anaerobic volumetric fraction, which is quantified by the soil redox potential (Eh). In DNDC, nitrification and denitrification, or CH_4 production and oxidation, occur in a soil simultaneously. The N_2O produced through nitrification outside of the balloon can diffuse into the balloon to participate in denitrification, and can be further reduced to N_2. The same is true for CH_4. The CH_4 produced within the balloon can diffuse into outside of the balloon to be oxidized. In general, nitrification and denitrification, or CH_4 production and oxidation, are both modelled in DNDC. The model tracks soil Eh evolution by simulating reductions of nitrate, Mn, Fe, and sulfate. Initial concentrations of the substrates can be defined by users, although DNDC provides default values of their geochemical background. The model has been validated against a number of field data sets observed in China, the USA, Japan, and Thailand and widely used over the last 10 years by many researchers (Brown *et al*., 2002; Butterbach-Bahl *et al*., 2004; Cai *et al*. 2003; Li *et al*., 1997; 2000; 2004; Smith *et al*., 2002; 2004). Simulated results showed that DNDC was able to simulate the basic patterns of NO, N_2O, CH_4 and NH_3 fluxes simultaneously (Li, 2000). This feature could be valuable in assessing the net effect of the changing climate or alternative agricultural management on either the atmosphere or agriculture.

Parameterization of the model

The ability of DNDC model to predict change in SOC and other parameters is driven by four drivers such as, climate, soil, vegetation and management practices. It is, therefore, important for a successful simulation to obtain adequate and accurate input parameters of these four drivers. The meteorological information (maximum and minimum temperature in ^{o}C and precipitation in cm) provide atmospheric datasets. We made changes in humus and humads to suit the model for simulation. It has been reported that soil system attain a quasi-equilibrium (QEV) after accumulation of dry matter as well as loss of SOC over time. After each change in land use system a period of constant management is required to reach a new QEV stage. Thus the SOC is stabilized to another QEV. Characteristics of that new land use pattern, vegetation cover and management practice. It has been reported that forest system attain QEV in 500 to 1000 years and agricultural systems nearly 5 to 50 years (Bhattacharyya et al., 2011). In the present study the Akola LTFE spot according to the above mentioned reports have attained a QEV over a period of nine years (1988-1997).

Calibration of the model

To fit the model to the data collected from the LTFE site the necessary first step was to prepare the climate files. The DNDC model requires day-wise maximum and minimum daily air temperature (^{o}C) and daily precipitation (cm). For Akola, we used 10 years weather data from 1988 to 1997. For soil, land use type, soil texture, bulk density, pH (water), SOC at surface soil (kg C kg^{-1}) (0-15 cm) were utilized as model inputs. The farming management practices for crop, tillage, fertilization, manure amendment, weeding, irrigation were the other inputs used from the published literatures (Rawankar *et al*., 2004).

Validation of the model

The DNDC model output was compared with field data to evaluate the performance of the model. The measured and estimated datasets can be compared qualitatively through graphs and quantitatively by a number of statistical tests. The statistical parameters selected are: the sample correlation coefficient (r), the standard deviation (SD), the root mean square error (RMSE) which is a measure of coincidence between measured and estimated values, M the mean difference between observations and simulations which gives indication of bias (or consistence error), and EF (modelling efficiency) (Smith *et al*., 1996). Quantitative evaluation was carried out for the period of 1988–1997 for Akola in terms of soil C. In the present study, DNDC model was used to predict the variables such as, soil organic carbon. Our exercise is restricted to the ability of the model to simulate the long term changes in soil organic carbon content. A schematic representation of statistical steps for evaluating the accuracy of a simulation and determination of acceptable errors is shown in figure 1. The crop yield estimated by DNDC was also compared with the measured yield of sorghum and wheat crops.

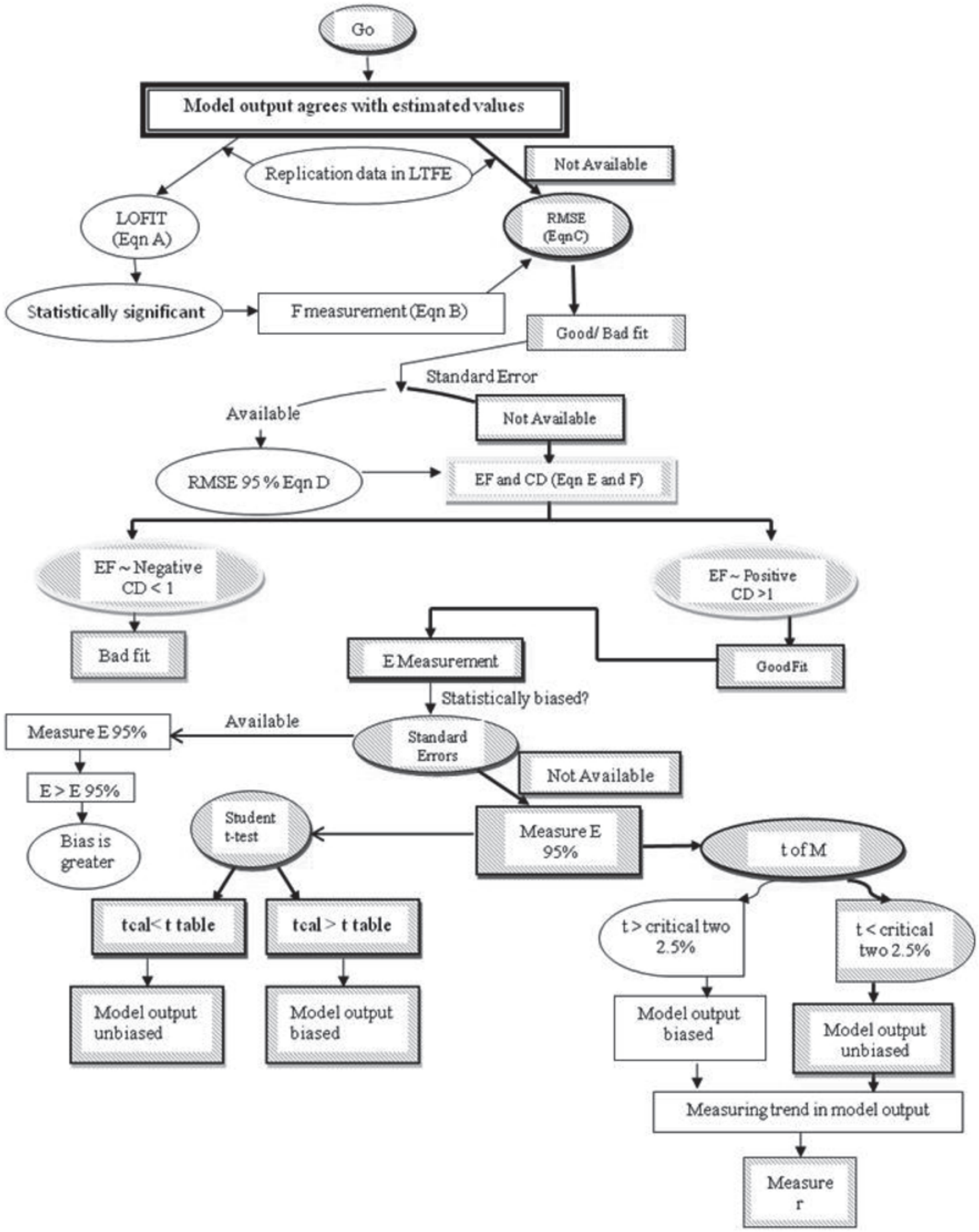

Figure 1 Quantitative comparision between predicted and modelled soil organic carbon - a statistical scheme (hatched tracks) were followed in our study) (Adapted from Smith *et.al,* 1997)

Results and Discussion

Estimating Total Organic Carbon

Total organic carbon was modelled for the surface horizon (0-15 cm). The modeling results indicated decrease in TOC in control plot with no application of fertilizers and manures (T1). Addition of 50% NPK (T2) marginally increased TOC value. Addition of 100% NPK mixed with FYM (T13) appreciably increased TOC on the contrary only FYM (without any inorganic) marginally increased TOC values (T14) (Fig 2; Tables 2, 3). The simulated results indicated that the SOC content at the control plot decreased

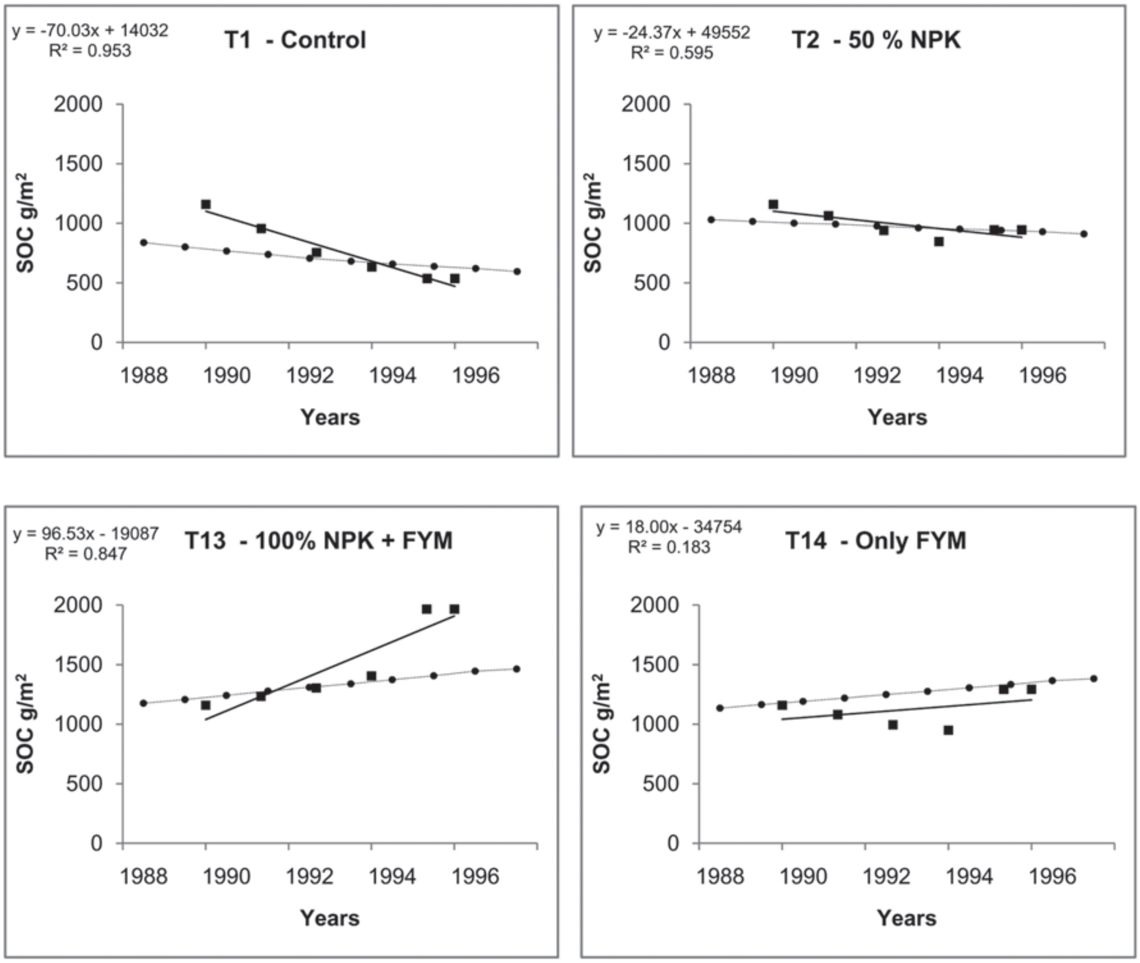

Figure 2 Differences in treatment effects (estimated vs. measured) for the Akola trial during experimental period (1988–1997)

Table 3 Comparison of measured and estimated yield of crops from Century and DNDC model

Century				DNDC			
Sorghum		Wheat		Sorghum		Wheat	
Measured	Estimated	Measured	Estimated	Measured	Estimated	Measured	Estimated
			T1 (Control)				
1.105	1.30	0.71	1.23	1.105	1.296	0.71	1.928
			T2 (50% NPK)				
2.208	3.10	2.623	2.11	2.208	1.412	2.623	2.327
			T13 (100% NPK +FYM)				
3.453	5.60	3.675	2.94	3.453	2.092	3.675	2.824
			T14 (Only FYM)				
1.876	1.18	1.934	0.37	1.876	2.007	1.934	2.051

while the SOC content at the manure amendment site substantially increased during the 10-year simulations. Model results indicated application of chemical fertilizer increased SOC through elevating the crop litter production as well directly adding organic matter into the soil (Jha *et al.*, 2012). The total simulation error in terms of RMSE ranged from 7 to 20% (Table 4). The simulation bias is expressed by ‘M’ was found to be not significant for all the treatments. However for T14, significant bias is observed when the values are compared on the basis of t of M (Table

Table 4 Model errors and simulation bias for experimental sites

Treatments	Simulation error					Simulation bias		SD[g]
	RMSE[a] t C ha^{-1}(%)	r[b]	M	t value of M[c]	Student'st[d]	significance of bias (yes/no)[e]	significance of bias (yes/no)[f]	
Akola (0-15cm)								
Control	1.59 (20)	0.97	0.65	1.01	0.60	no	no	1.6
T2 (50% NPK)	0.76 (7)	0.77	0.17	0.53	0.36	no	no	0.8
T13 (100%NPK+FYM)	2.96 (19)	0.92	1.72	1.59	1.09	no	no	2.6
T14 (Only FYM)	1.89 (16)	0.42	-1.42	-2.54	-1.98	yes	no	1.4

[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 2.23

[d]Student's 't' = $\frac{Mean\ of\ measured\ value - Mean\ of\ modelled\ value}{\sqrt{Variance\ of\ observed\ value + Variance\ of\ modelled\ value/n}}$

[e]On the basis of t of M; [f]On the basis of Student's 't'; [g]Standard Deviation (SD) of measured values

4). In all the cases the deviation of the simulated value from the observed value was less than 5% except in case of T14 (only FYM) when the bias was found significant. Thus the model was able to simulate the changes in total organic carbon satisfactorily. The simulation correlation coefficient (r) ranged from 0.42 to 0.97. Fig. 2 show the modelled yield for two crops (sorghum and wheat) in Akola. The r^2 values of wheat shows a reasonably good association; for sorghum this values was 0.488. When the estimated and measured values of crop yields are plotted on 1:1line, it was found that the model could simulate satisfactorily against the measured values of 1800-2000 kg ha^{-1} (Fig. 3) with correlation coefficient of 0.70 and 0.95 for sorghum and wheat crops, respectively. Earlier the Century model was parameterized using regional crop data across the Indo-Gangetic Plains (IGP) (Bhattacharyya *et al.*, 2007) and the semi-arid sites of India dominated by black soils (Vertisols) (Bhattacharyya *et al.*, 2010).

Estimating Crop Yields for sorghum and wheat

We earlier made an attempt to develop a set of completely different crop files for the Indo-Gangetic Plains and the black soil regions for parameterzing Century model (Bhattacharyya *et al.*, 2007, 2010). We made similar attempt for DNDC model. However the built in crop information in DNDC helped us to reach the measured average crop yield for sorghum and wheat. Interestingly the control treatment in wheat, inspite of best efforts through parameterization process, did not produce satisfactory value (Table 3). Estimated and measured average crop yield of two crops (sorghum and wheat) are shown in figure 2. DNDC model simulated wheat yield better than sorghum yield (Fig. 4).

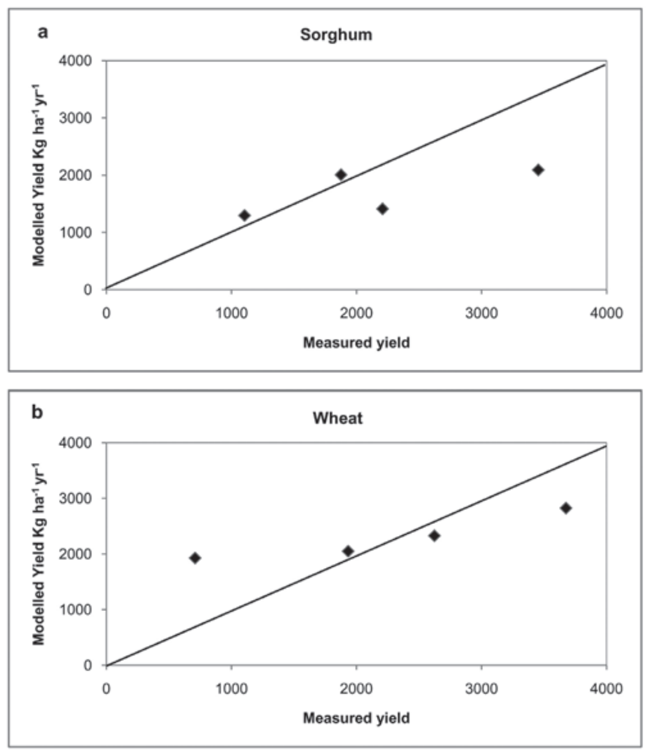

Figure 3 Estimated vs. measured yield from DNDC model in semi-arid site of the Akola experimental spots: (a) sorghum, (b) wheat

General Discussion

DNDC appeared to model changes in TOC more successfully in treatments when manures were applied only (T14) or in combination with 100%NPK or only with 50% NPK (T13 and T2) (Table 5). Inspite of best efforts with the iteration process SOC estimation before experiment did not match with the SOC measured values. It seems probable

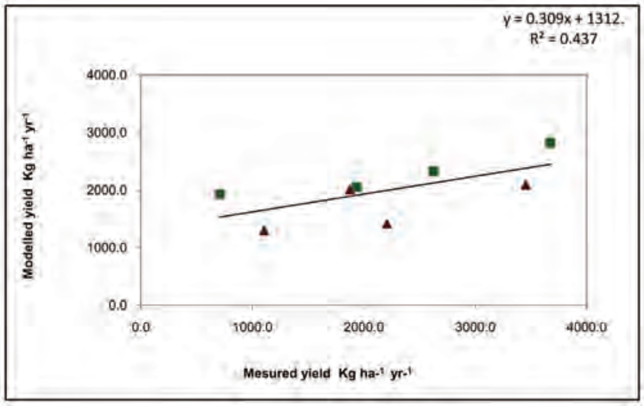

Figure 4 Estimated vs. measured yield from DNDC model in semi-arid site of the Akola experimental spots for both sorghum and wheat

that DNDC model could not capture the initial TOC values in plots without any inorganic and organic amendments.

<Table 5>

There are many examples of comparison exercises between models (Smith *et al*., 1997). Earlier Akola site was modelled for Roth*C* (Bhattacharyya *et al*., 2011) and by Century (Bhattacharyya *et al*., 2010) (Tables 5 and 6). The comparison of TOC data shows fairly very good agreement between SOC measured and estimated values in two different times scale. The Century, however, underestimates SOC in T2 (50%NPK), T13 (100%NPK+FYM) and T14 (only FYM). Akola site did not provide historical details on native vegetation. Generic or best guess histories prior to the start of the experiment underestimated the soil carbon during the end of experimental period. This offset in the initial carbon status might have influence on the entire simulation process of the experiment. There are other concerns also such as, lack of bulk density data throughout the experimental period and an apparent mismatch in analytical techniques of measuring organic carbon in soils in the beginning and at the end of the experiment (Bhattacharyya *et al*., 2010).

As compared to Roth*C* and Century, DNDC was able to capture the events of LTFE in T14 (only FYM). In the beginning, the model underestimates SOC in control (T1) and 50% NPK (T2) treatments (Table 5), while for 100%NPK+FYM (T13) model underestimates at the end of the experiment (Table 5). It seems that in absence of fertilizers and manure the DNDC model fails to get the correct lead for initiating for Akola site. However this degree of underestimation is slightly narrowed down when 50% NPK is added. In case of combined dose of inorganic and organic, the model initiates well but fails to simulate at the end of experiment largely due to excess of inorganics. This finds support from the observation in T14 where only FYM (T14) is applied (Table 5).

Performance of DNDC model for T2 (50% NPK) treatment is quite satisfactory with RMSE absolute value 0.76 t C ha^{-1} which is less than 10% of mean observed soil carbon. However, in the treatments of T1 (Control), T13 (100%NPK + FYM) and T14 (Only FYM) is not satisfactory. In the case of T14 (Only FYM) the difference in estimated and measured soil carbon is 88 g/m^2 which could be due to experimental error (Fig 5).

Among the three models *viz*. RothC, Century and DNDC, the performance of Roth*C* model appears more promising than other two models in all the treatments with

Table 5 Comparison of measured and estimated SOC from Roth*C*, Century and DNDC model

(Values in g/m^2)

RothC[1]				Century[2]				DNDC[4]			
SOC m[a]		SOC e[b]		SOC m		SOC e		SOC m		SOC e	
BE[c] (1988)	AE[d] (1997)	BE (1988)	AE (1997)	BE[c] (1988)	AE (1997)	BE (1988)	AE (1997)	BE (1988)	AE (1997)	BE (1988)	AE (1997)
T1 (Control)											
1105	1075	1100	1070	1159	537	1168	538	1159	537	838	595
T2 (50% NPK)											
1105	1080	1100	1075	1159	945	1184	808	1159	945	1029	910
T13 (100% NPK +FYM)											
1105	1193	1202	1290	1159	1966	1184	1507	1159	1966	1175	1463
T14 (Only FYM)											
1105	1497	1196	1588	1159	1293	1185	947	1159	1293	1134	1381

[a]SOC m : SOC measured; [b]SOC e : SOC estimated; [c]BE: Before experiment; [d]AE: After experiment; [1]RothC considers 23 cm soil depth:wetook15 cm soil depth; [2]Century considers 20cm soil depth; [3]InfoCrop considers 23 cm soil depth [4]DNDC considers 23 cm soil depth.

Table 6 Comparison of Roth*C*, Century and DNDC model performance in Akola

Details of Treatments	Simulation Error					
	RMSE t C ha^{-1} (%)			t value of M		
	Roth*C*	Century	DNDC	Roth*C*	Century	DNDC
Control (T1)	0.19 (1.79)	0.13 (1.74)	1.59 (20.85)	0.98	-0.11	1.01
50% NPK (T2)	0.36 (3.26)	3.85 (39.05)	0.76 (7.71)	0.47	0.25	0.53
100% NPK+FYM @10t ha^{-1} (T13)	0.95 (8.01)	2.71 (18.01)	2.96 (19.80)	0.31	1.40	1.59
FYM@10t ha^{-1}	0.91 (6.08)	1.98 (17.58)	1.89 (16.83)	0.05	0.97	-2.54

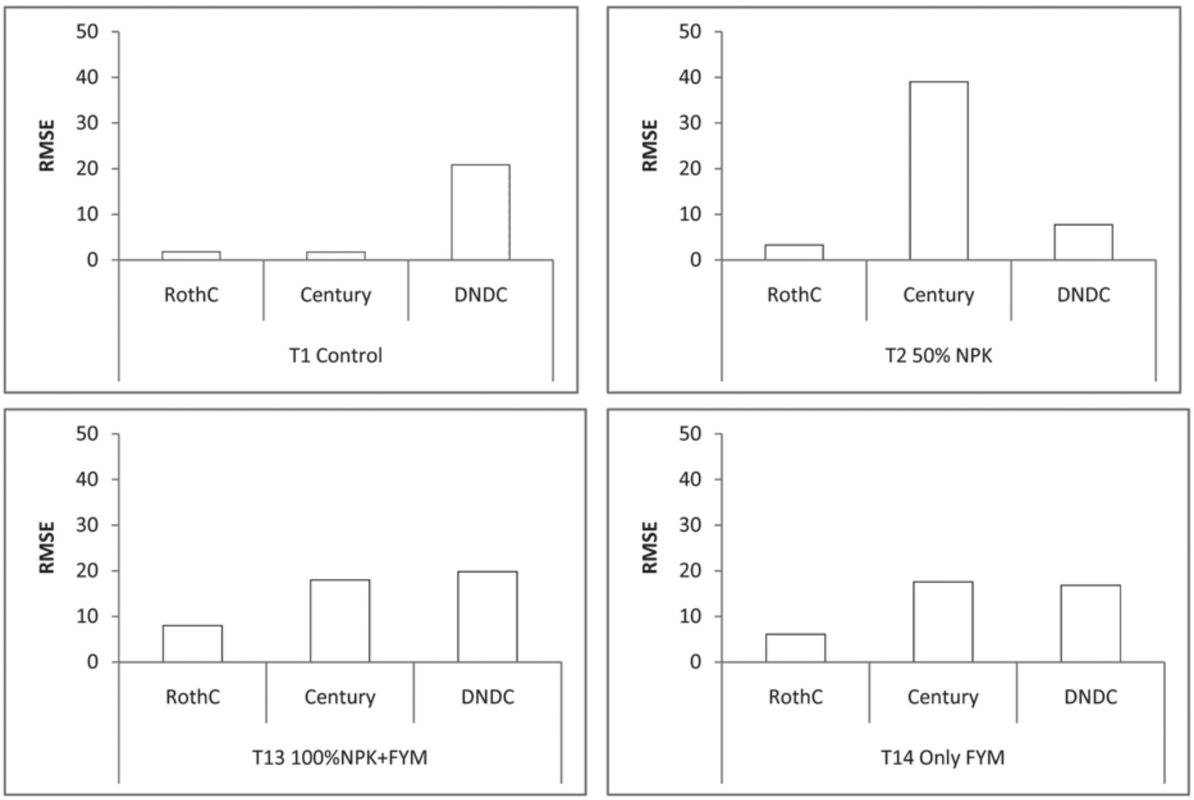

Figure 5 Relative performance of Roth*C*, Century and DNDC models showing root mean square error (RMSE)

RMSE values less than 10% of the mean measured value. Another statistical evaluation criterion i.e. t values of M were found to be non-significant at 5% significant level except T14 (Only FYM) treatment for DNDC model (Table 6).

Conclusion

The study presents attempt to parameterize the DNDC model including soil and farming management files for application to sorghum-wheat cropping systems of high clay soils in Akola, Maharashtra. DNDC can simulate the treatment effects although its performance is satisfactory only in 50% NPK treatment (T2). Comparison of three models such as, Roth*C*, Century and DNDC indicates Roth*C* to perform well in Akola.

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