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ORIGINAL ARTICLE

Validation of soil organic carbon dynamics model in the semi-arid tropics in Niger, West Africa

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Abstract The fertility of sandy soils in the Sahelian zone (SZ) is extremely low. This poor soil fertility is one of the limiting factors of crop production in the SZ. Therefore, it is imperative to improve or to maintain soil fertility through various agricultural management methods. Further, it is well known that soil organic matter plays an important role in improving the physico-chemical properties of these sandy infertile soils. Therefore, it is essential to develop a suitable tool for the appropriate evaluation of soil organic carbon (SOC) dynamics in the SZ. Therefore, the Rothamsted carbon model (Roth-C) was verified in 32 treatments of two long-term field experiments with and without crop residue application. These experiments were performed by ICRISAT. The performance of the model was evaluated by statistical methods using four indices (*RMSE*: root mean square error, *LOFIT*: lack of fit, *r*: correlation coefficient, and *M*: mean difference). As a result, the predicted SOC values in the case without crop residue management decreased with time in approximately 10 cultivated years. In contrast, in the case with crop residue application, the predicted SOC remained roughly equal to the initial SOC value during the term observed. Mostly, the Roth-C-modelled values agreed well with the actual value. *RMSE* and *LOFIT*, the statistical indicators of agreement between predicted and observed values, showed a significant conformity between the predicted and observed SOC values in all the 32 treatments. This fact means that Roth-C can estimate long-term SOC dynamics of several technical options that developed with short-term trials. Moreover the annual carbon requirement for SOC maintaining can be calculate if enough number of cases was estimated. And also analysis of regional carbon dynamics was made possible with using Roth-C model. It will contribute to show the sustainable development in SZ against global warming and other climatic changes.

Keywords Rothamsted carbon model · Niger · Soil organic carbon · Long-term experiment

Introduction

Soil organic carbon (SOC) dynamics is one of the most important topics in the study of sustainable

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agriculture in the semi-arid Sahelian zone (SZ). It is well-known that soil organic matter (SOM) plays an important role in crop productivities in the infertile sand soil in this region (Bationo and Buerkert 2001; Franzluebbers et al. 1994; De Ridder and Van Keulen 1990). However, the physical and chemical functions of SOM, particularly in the long-term, are insufficiently understood, because of lack of information on their dynamics in this area. Therefore, it is imperative to enhance information collection through long-term research activities. Several investigations of soil fertility management have been carried out for the development of appropriate agricultural techniques for Niger (Schlecht et al. 2004; Bationo et al. 1998; Hayashi et al. 2009). However, the sustainability of these technical options should be verified before encouraging farmers to implement them. A model approach can support the assessment of the sustainability of agro-ecosystems. Moreover, the model will elucidate the dynamics of SOC with respect to the agro-ecosystem in the SZ.

Many models are available for the estimation of SOM turnover (McGill 1996; Coleman and Jenkinson 1996; Li et al. 1992). Among these models, the Rothamsted carbon model (Roth-C) is one of the most widely used models for the simulation of SOC dynamics under different environmental conditions and management methods (e.g. Shirato and Yokozawa 2005; Shirato et al. 2004; Falloon et al. 1998b). However, the Roth-C model has hardly been used under tropical semi-arid conditions, particularly in the SZ of West Africa. Therefore, this study aims to verify the Roth-C model in the SZ of West Africa. Verification of the model requires agreement between the dynamics of predicted and observed SOC values. Thus, we investigated the capability of the model to reproduce actual SOC values in two long-term field experiments that were carried out at Sadore, ICRISAT West and Central Africa (ICRISAT-WCA) under Nigerian environmental conditions.

Materials and methods

Study site

The study was conducted in ICRISAT-WCA located in Sádore, 45 km south of Niamey, Niger (13° 15′ N, 13° 15′ E), at an altitude of 240 m above sea level. The climate of Sádore is characterized by a short rainy season from June to September (Subbarao et al. 2000, Sivakumar 1986), with an annual average precipitation of approximately 560 mm. Monthly mean precipitation and evaporation are shown in Fig. 1. The study site is located on a sandy plain with aeolian sands (depth: 2–8 m), covering a series of stepped surfaces composed of cemented laterite gravels (West et al. 1984). The soil has been classified as *Psammentic Paleustalf* according to the USDA soil taxonomy.

Experiment 1 was initiated in 1983 for evaluating the long-term effect of the application of crop residues, chemical fertilizer, and a combination of both, on the growth of pearl millet (*Pennisetum glaucum* (L.) R. Br.). The site was divided into four plots—crop-residue-applied (CR) plots, chemical-fertilizer-applied (F) plots, crop-residue-and-chemical-fertilizer-applied (CR + F) plots, and a control plot (Control). Millet cultivation was rotated with cowpea (*Vigna unguiculata* (L.) Wlp.) in each plot. Millet residue consisting of the above-ground stalks and leaves of the millet grown on the same plot in the previous year, was applied as surface mulch. Phosphorus [as simple-super phosphate (SSP)] and nitrogen (as urea) were applied annually at rates of 13.0–30 kg ha^{-1}, respectively. All treatments were replicated four times in a randomized complete block design (RCBD). Many studies on the effects of crop residue application have been conducted in Niger (Bationo and Mokwunye 1991; Hafner et al. 1993; Rebafka et al. 1994). Results from Experiment 1 have

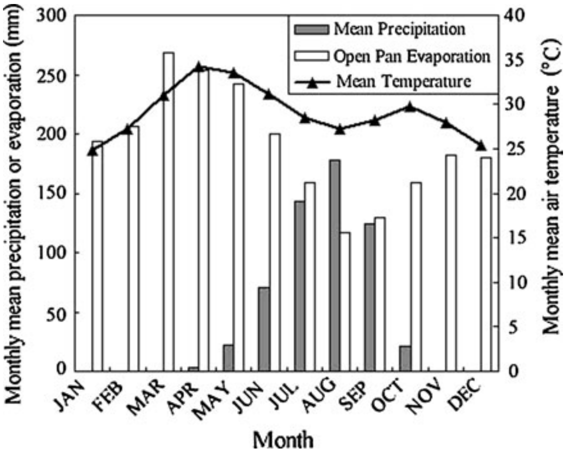

Fig. 1 Monthly means of air temperature, precipitation, and evaporation from 1998 to 2008, at ICRISAT-WCA, Niger

been reported earlier: For example, Bationo (1987) reported that the yield in CR was four times that in the Control, and CR + F showed a three times higher biomass yield than CR and/or F. Geiger et al. (1992) suggested that the increase in crop production, following the application of the millet residue as surface mulch, could be due to recycling of nutrient elements from the residue or the effect of the residue on the entrapment of soil materials or on the stabilization of the surface soil.

Experiment 2 (Subbarao et al. 2000) was initiated in 1986 for investigating the long-term effect of pearl millet and cowpea cultivation under different management methods, i.e. phosphorus (P) fertilizer application, rotation, intercropping, tillage, and their combinations. The experiment consisted of fourteen treatments based on RCBD with four replications (Subbarao et al. 2000). All 14 treatments include four sub-plots, divided into those with and without the application of nitrogen (N) fertilizer and crop residue. In this study, sub-plots without N fertilizer application were selected for observing the changes in SOC for testing the performance of the Roth-C model.

Soil samples for chemical analysis were collected in June and October, i.e. before and after the crop season, at a depth of 0–15 cm at Site 1 and 0–20 cm at Site 2. Yields of millet and cowpea were recorded.

Procedure of soil analysis

Soil samples were air-dried for 1 week, followed by crushing and sieving through a 2-mm sieve. Organic carbon (Org-C) in the soil was determined using the Walkely-Black method (see Nelson and Sommers 1982). Concentrated H_2SO_4 was added to a mixture of soil and aqueous solution of 0.167 mol L^{-1} $K_2Cr_2O_7$. The heat generated by mixing H_2SO_4 and H_2O increased the temperature sufficiently to oxidize the organic matter within the first 5 min. After waiting for 30 min, the residual $K_2Cr_2O_7$ was titrated against a solution of 0.025 mol L^{-1} $FeSO_4$. Carbon contents of the crop and the crop residues were also determined by the Walkely-Black method.

Model setup

To simulate SOC dynamics, Roth-C model version .26.3 (Coleman and Jenkinson 1996) was used. The model simulates SOC dynamics on the basis of four active SOC pools, i.e. decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM), and inert organic matter (IOM) as one non-active pool. For modelling each set of experimental data, we set the initial SOC content as that measured at the beginning of each experiment and simulated SOC dynamics for the 0–15 cm soil depth in Experiment 1 and 0–20 cm in Experiment 2, for each management scenario. These initial SOC contents (Mg C ha^{-1}) were calculated from the analyzed SOC concentration and bulk densities. The initial allocation of SOC in each of the five compartments (DPM, RPM, BIO, HUM, and IOM) was calculated on the basis of results of previous studies (Coleman and Jenkinson 1996; Jenkinson et al. 1999; Shirato and Yokozawa 2005), i.e. we assumed that the SOC pools were in equilibrium. Roth-C can be run inversely to calculate how much C needs to be added to the soil annually to maintain a specific level of SOC. In the calculation process, in order to simulate the equilibrium condition, the amount of SOC allocated to each of the five compartments was also calculated. We ran the model inversely for 10,000 years to calculate the amounts of C input required to establish the SOC content at the beginning of each experiment and to set the SOC contents in the five compartments to the equilibrium situation. This C input was divided equally over 12 months according to Coleman and Jenkinson (1996). Soils were assumed to be covered with vegetation throughout the year before the start of the experiments. The assumptions on the temporal distribution of C input and on soil cover did not affect the simulation results in the course of the experiments, because the same initial SOC content could result from different temporal distributions of C inputs or soil cover. A DPM:RPM ratio of 1.44, i.e. a value typical for most agricultural crops and grass (Coleman and Jenkinson 1996), was applied. IOM shown in Table 1, was calculated according to: $\mathrm{IOM} = 0.049 \times \mathrm{SOC}^{1.139}$ (Falloon et al. 1998a). Monthly mean air temperatures, monthly precipitation, and monthly open pan evaporation were obtained from ICRISAT-WCA over the period of the long-term experiments. In all cases, the rate-modifying factor for soil moisture in Roth-C was calculated to the minimum value of 0.2 during the dry season and the maximum value of 1.0 during the

Table 1 Summary of long-term experiment at Site 1

Plot	Management	C top	Initial SOC mg C ha^{-1}	IOM mg C ha^{-1}	Annual C input mg C ha^{-1}
Control	Sole/Flat/Rotation	Millet/Cowpea	3.44	0.20	0.07
CR	Sole/Flat/Rotation	Millet/Cowpea	3.81	0.22	0.51
F	Sole/Flat/Rotation	Millet/Cowpea	3.84	0.23	0.17
CR + F	Sole/Flat/Rotation	Millet/Cowpea	4.05	0.24	1.17

rainy season (From July to September). Once the initial SOC content and its initial allocation to each of the five compartments were established, the model was run until 2008 for Experiment 1 and until 1995 for Experiment 2.

Statistical analysis of model performance

For evaluation of model performance, the agreement between predicted and observed SOC values was established through statistical analyses. Four statistical indices—correlation coefficient (*r*), mean difference (*M*), lack of fit (LOFIT), and root mean square error of the model (RMSE)—were calculated, using MODEVAL ver.2.0 (Smith et al. 1997):

$$r = \frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}$$

$$M = \frac{\sum_{i=1}^{n}(Oi - Pi)}{n}$$

$$\mathrm{LOFIT} = \sum_{i=1}^{n} m_i(O_i - P_i)^2$$

$$\mathrm{RMSE} = \frac{100}{O} \times \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}$$

where, *O* is observed SOC (Mg C ha^{-1}), *P* is the predicted SOC value, and *m* is the number of replications. And suffix *i* indicates the mean value of replications, over bars indicates average of all value in each treatment, respectively.

The statistical indicator *M* indicates the bias of the modelled value against the measured value. Further, LOFIT indicates the uncertainty of agreement between the predicted and the observed values. RMSE provides the percentage term for the total difference between predicted and observed values.

Results and discussion

Model performance at Site 1

The initial conditions of the soil before the beginning of the long-term experiment in Site 1 are listed in Table 1. Initial SOC content ranged from 3.44 to 4.05 Mg C ha^{-1} at Site 1. The predicted annual C inputs required to establish the initial SOC allocations of the five components at equilibrium varied from 0.54 to 0.63 Mg C ha^{-1}. The initial SOC content and its allocations, calculated by using the Roth-C inverse mode, showed a difference of 0.6 Mg C ha^{-1} in SOC content between highest and lowest value in Site 1.

The statistics quantifying the degree of agreement between modelled and observed SOC at Site 1 are given in Table 2. The correlation coefficient (*r*) did not show significant correlations for any of the treatments at Site 1, because the SOC concentration at this site was extremely low and showed little fluctuations. Therefore, it can be considered that low *r* is not a serious problem for model performance in the SZ. The *M* value, indicating the bias of the simulated value against the observed value, showed a significantly positive value in the case without crop residue application. In contrast, in the case with crop

Table 2 Statistical analysis of agreement between predicted and observed SOC values at Site 1

Plot	*r*	*M*	LOFIT	RMSE (%)
Control	0.28 n.s.	0.75	45.90 n.s.	29.59 n.s.
CR	0.50 n.s.	0.09 n.s.	11.07 n.s.	12.65 n.s.
F	0.42 n.s.	0.65	34.38 n.s.	22.97 n.s.
CR + F	0.06 n.s.	−0.48 n.s.	32.67 n.s.	17.46 n.s.

r Correlation Coeff, *M* Mean Difference, *LOFIT* Lack of Fit, *RMSE* Root mean square error of model, *n.s.* not significant residue application, the *M* value did not show a significant bias. This result implies that Roth-C underestimated SOC value for the treatment without crop residue application, suggesting inaccuracies in model parameters. RMSE of Control and F plots showed relatively higher value than crop residue added plots. It means the accuracy of model calculation of non-crop residue treatments are less than crop residue treatments. This fact shows the possibility that there are some discriminative parameters caused as the results of continuous cropping without organic matter application, in these plots.

However, LOFIT and RMSE as indicators of disagreement between modelled and observed SOC did not show a significant error, implying satisfactory model performance in this experiment.

The predicted SOC contents in the Control and F plots decreased with time in approximately 10 cultivated years (Fig. 2). In contrast, the predicted SOC contents in the two plots with crop residue application did not show a clear decrease during the 25 years of the experiment (Fig. 2). In particular, in the CR + F plot, simulated SOC clearly exhibited an increasing trend. The annual C input in the CR + F plot was markedly higher than those in the other plots. Crop residue application has been shown to increase the yield of crops (e.g. Bationo 1987). As a result, annual mean C inputs in the plots with crop residue application (CR and CR + F) were higher than in those without crop residue application (Table 1). In particular, in the CR + F plot, yield seemed to be affected by the effect of nutrient supply from crop residue and chemical fertilizer or by the effect of improvement in the physical soil properties due to organic matter application. These higher annual C inputs resulted in the increasing trend in Roth-C-calculated SOC contents. SOC contents in CR remained essentially constant, as the estimated annual C input required for maintaining the initial SOC value was similar to the observed value.

Some previous studies have shown that a combination of crop residue and chemical fertilizer application result in yield increases (Bationo and Mokwunye 1991; Muehlig-Versen et al. 1997). Our model approach showed a positive effect of the combined application on SOC accumulation. However, from the perspective of the farmers in Niger, the use of chemical fertilizers and retainment of all crop residues in the field are difficult to realize, because these farmers normally do not have sufficient money to purchase chemical fertilizers and they use the crop residues for cooking, for construction, and as animal feed (Nicou and Charreau 1985). Therefore, a combined application of chemical fertilizer and crop residue seemed to be impractical for these farmers.

Model performance at Site 2

Because of the different soil depths considered at the two sites, the absolute SOC values at the two sites cannot be directly compared, but their dynamics can.

In the treatments with crop residue application at Site 2, initial SOC contents ranged from 3.54 to 6.10 Mg C ha^{-1}, and the predicted annual C inputs

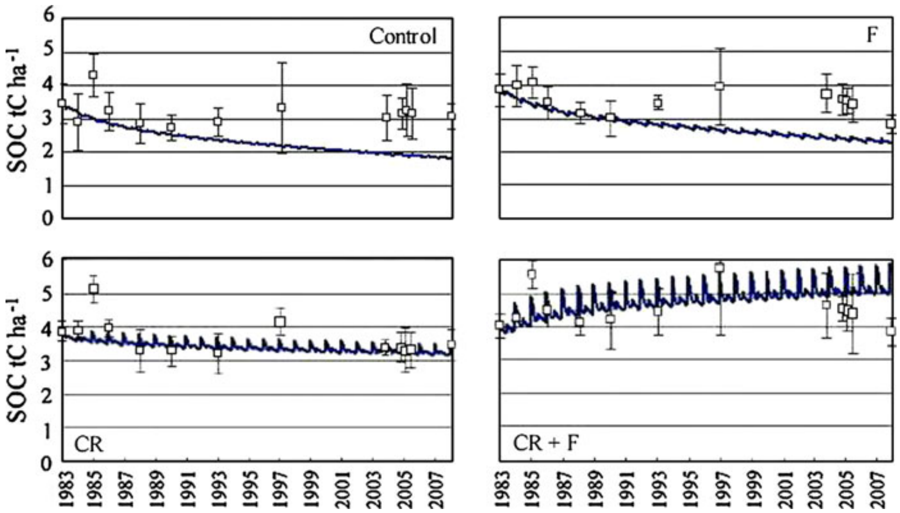

Fig. 2 Predicted (*line*) and observed (*dots*) SOC changes in long-term experiment at Site 1. *Error bars* in each box indicate standard deviations in 4 replications

Table 3 Summary of long-term experiment at Site 2

	Plot Management	Crop	Without crop residue application			With crop residue application		
			Initial SOC mg C ha^{-1}	IOM mg C ha^{-1}	Annual C input mg C ha^{-1}	Initial SOC mg C ha^{-1}	IOM mg C ha^{-1}	Annual C input mg C ha^{-1}
1	Traditional Practice with Improved Variety	Millet	3.69	0.36	0.03	3.94	0.23	0.37
2	Intercropping/Ridge/ No Rotation	Millet/Cowpea	6.32	0.40	0.10	4.55	0.28	1.03
3	Intercropping/Ridge/ Rotation 1[a]	Millet/Cowpea	5.96	0.37	0.17	4.99	0.31	0.87
4	Intercropping/Ridge/ Rotation 2[b]	Millet/Cowpea	6.14	0.39	0.13	4.96	0.30	0.66
5	Intercropping/Flat/ No Rotation	Millet/Cowpea	5.33	0.33	0.07	4.06	0.24	0.96
6	Intercropping/Flat/ Rotation 1[a]	Millet/Cowpea	5.65	0.35	0.13	4.07	0.24	0.77
7	Intercropping/Flat/ Rotation 2[b]	Millet/Cowpea	5.32	0.33	0.10	4.20	0.25	0.60
8	Sole/Ridge/No Rotation	Millet	5.65	0.35	0.10	4.47	0.27	0.97
9	Sole/Ridge/Rotation 1[a]	Millet/Cowpea	6.22	0.40	0.17	5.61	0.35	1.02
10	Sole/Ridge/Rotation 2[b]	Millet/Cowpea	5.22	0.36	0.14	5.11	0.31	0.93
11	Sole/Flat/No Rotation	Millet	5.47	0.34	0.09	3.54	0.21	0.90
12	Sole/Flat/Rotation 1[a]	Millet/Cowpea	6.23	0.39	0.17	4.84	0.30	0.87
13	Sole/Flat/Rotation 2[b]	Millet/Cowpea	5.38	0.33	0.10	3.85	0.23	0.73
14	Traditional Practice with Local Variety	Millet	7.03	0.45	0.07	6.10	0.38	1.14

[a] Rotation1: Millet cultivation in even years

[b] Rotation2: Millet cultivation in odd years

for maintaining these initial values varied from 0.55 to 0.94 Mg C ha^{-1} (Table 3). In the treatments without crop residue application, initial SOC contents ranged from 5.33 to 7.03 Mg C ha^{-1}, and the average of the 14 treatments was 5.88 Mg C ha^{-1}. Predicted annual C input in this situation to maintain the SOC-contents was 0.91 Mg C ha^{-1} on average.

The SOC dynamics at Site 2 are shown in Figs. 3 and 4, respectively, the statistical indicators quantifying agreement between modelled and observed values are given in Table 4. LOFIT and RMSE for the situations without crop residue application showed relatively higher values than for the situations with crop residues; however, they all showed good agreement; i.e. in none of the treatments, there were significant deviations between simulated and observed values. These results imply that Roth-C satisfactorily simulates SOC dynamics, irrespective of the cropping systems—tillage, rotation, intercropping, and their combinations.

The correlation coefficient *r* did not show significant values for the situations with crop residue application, but showed significant positive values for those without crop residue application. The correlation coefficient also indicated a linear relation between the modelled and observed values. For the situations without crop residue application, a clear decreasing trend in SOC was observed, whereas SOC remained essentially constant for the situations with crop residue application. The latter leads to the lack of a significant value for the correlation coefficient. Therefore, it can be considered that low *r* is not a serious problem for model performance in the SZ; however, it may cause difficulty in carrying out a highly accurate assessment in the case of crop residue application management.

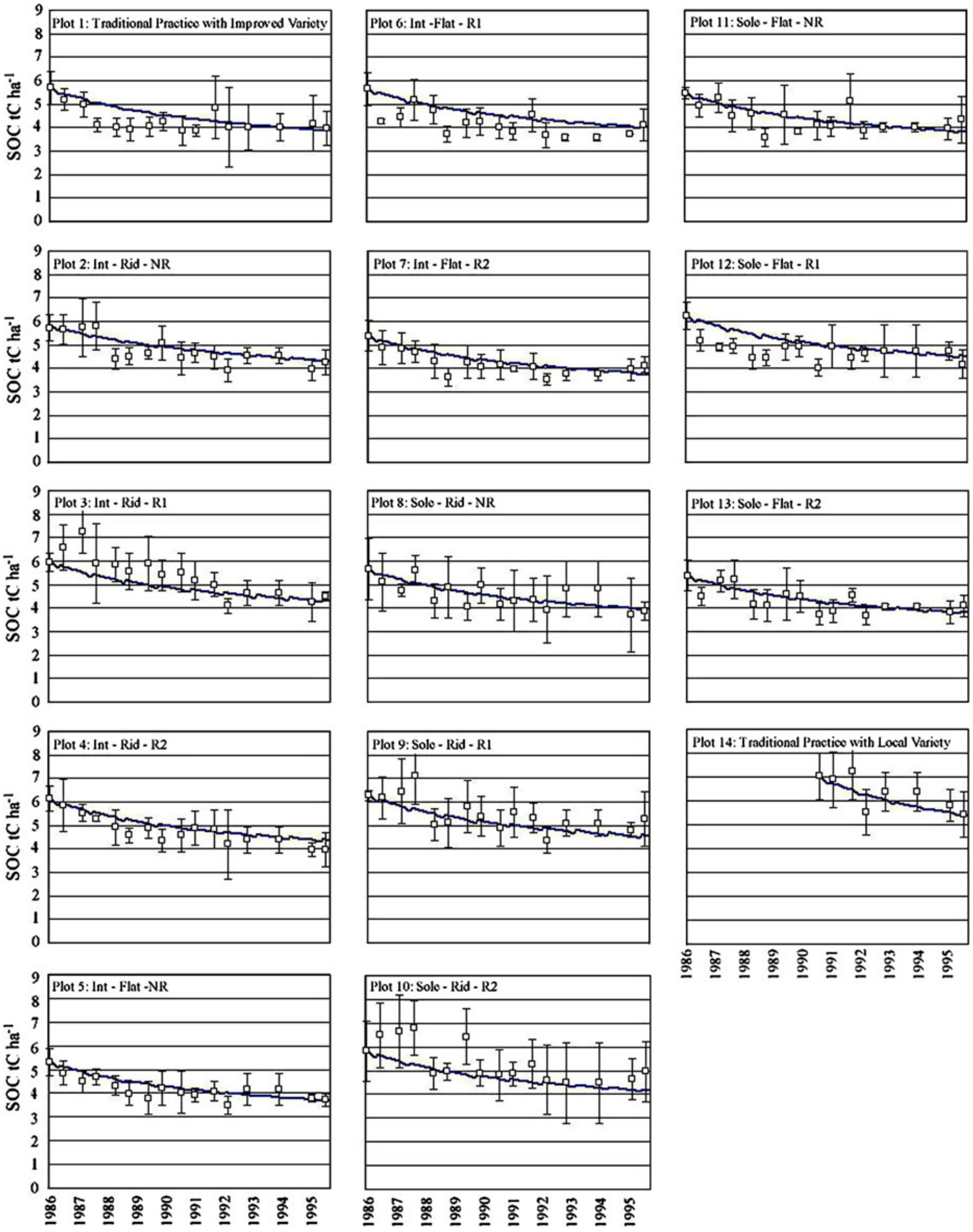

Fig. 3 Predicted (*line*) and observed (*dots*) SOC changes in long-term experiment without crop residue application at Site 2. *Error bars* in each box indicate standard deviations of 4 replications

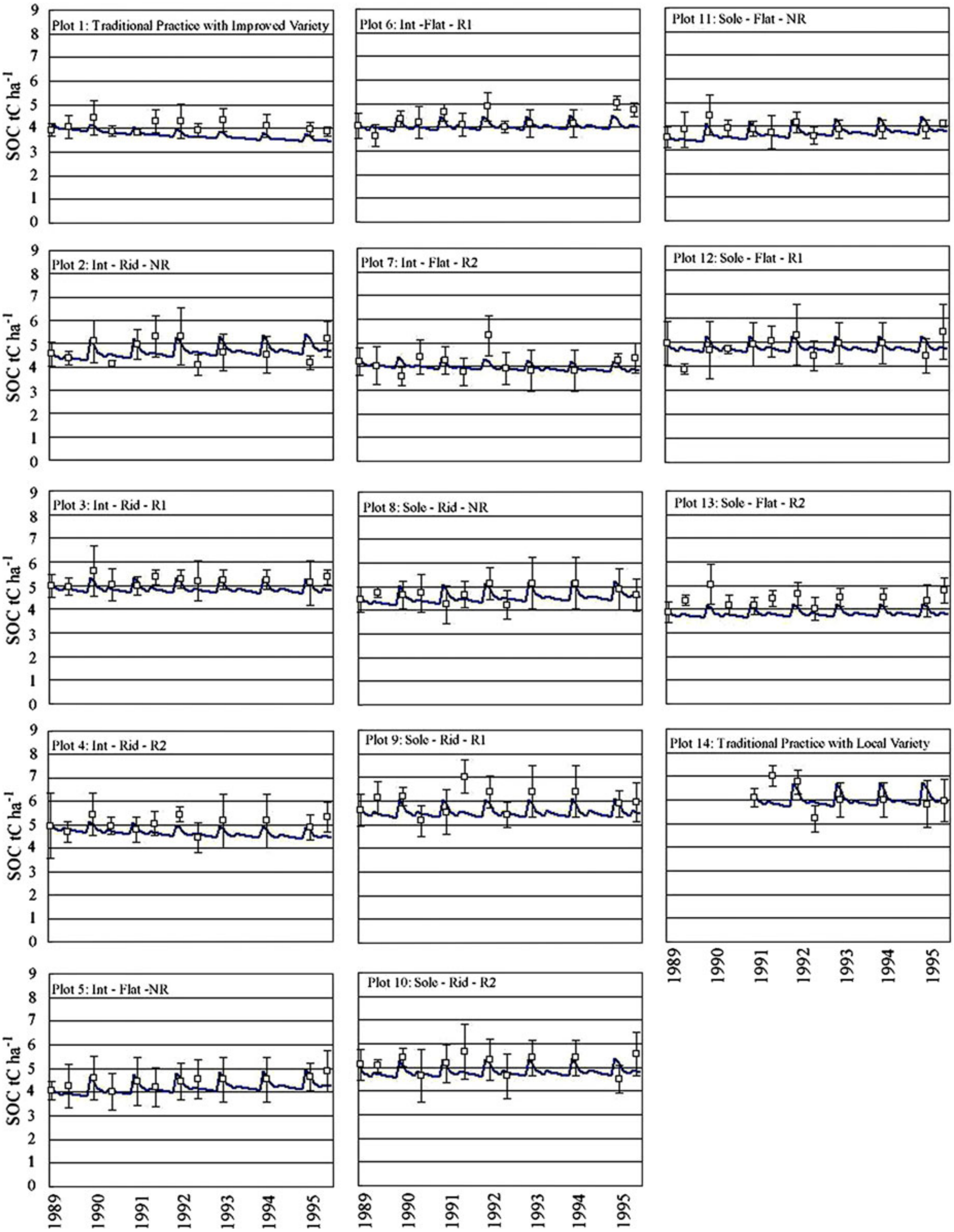

Fig. 4 Predicted (*line*) and observed (*dots*) SOC changes in long-term experiment with crop residue application at Site 2. *Error bars* in each box indicate standard deviations in 4 replications

Table 4 Statistical analysis of agreement between predicted and observed SOC values at Site 2

Plot	Without crop residue application				Crop residue application			
	r	*M*	LOFIT	RMSE (%)	*r*	*M*	LOFIT	RMSE (%)
1	0.78	−0.07 n.s.	10.19 n.s.	8.81 n.s.	0.15 n.s.	0.27	7.08 n.s.	9.36 n.s.
2	0.83	−0.17 n.s.	12.28 n.s.	8.73 n.s.	0.20 n.s.	−0.13 n.s.	11.36 n.s.	10.34 n.s.
3	0.85	0.62	44.52 n.s.	14.79 n.s.	0.13 n.s.	0.17	3.90 n.s.	5.49 n.s.
4	0.95	−0.05 n.s.	5.48 n.s.	5.80 n.s.	0.19 n.s.	0.23	6.97 n.s.	7.58 n.s.
5	0.90	0.08 n.s.	7.18 n.s.	7.53 n.s.	0.57 n.s.	0.07 n.s.	3.00 n.s.	5.64 n.s.
6	0.82	−0.24 n.s.	14.39 n.s.	10.66 n.s.	0.56 n.s.	0.15 n.s.	6.19 n.s.	8.29 n.s.
7	0.89	0.00 n.s.	5.44 n.s.	6.56 n.s.	0.03 n.s.	0.05 n.s.	9.48 n.s.	10.71 n.s.
8	0.66	0.10 n.s.	13.92 n.s.	9.81 n.s.	0.48 n.s.	0.01 n.s.	3.98 n.s.	6.10 n.s.
9	0.70	0.42	28.74 n.s.	11.76 n.s.	0.18 n.s.	0.30 n.s.	16.52 n.s.	9.76 n.s.
10	0.71	0.66	51.77 n.s.	16.26 n.s.	0.10 n.s.	0.18 n.s.	9.22 n.s.	8.50 n.s.
11	0.70	0.09 n.s.	12.16 n.s.	9.51 n.s.	0.32 n.s.	0.05 n.s.	4.23 n.s.	7.60 n.s.
12	0.79	−0.20 n.s.	12.01 n.s.	8.62 n.s.	0.21 n.s.	−0.19 n.s.	10.25 n.s.	9.75 n.s.
13	0.84	0.11 n.s.	8.84 n.s.	8.14 n.s.	0.27 n.s.	0.45	14.69 n.s.	12.56 n.s.
14	0.75	0.18 n.s.	7.17 n.s.	7.46 n.s.	0.00 n.s.	−0.12 n.s.	11.62 n.s.	9.87 n.s.

r Correlation Coeff, *M* Mean Difference, *LOFIT* Lack of Fit, *RMSE* Root mean square error of model, *n.s.* not significant

The *M* value showed a significant positive value, which implies that the model significantly underestimated SOC-values, in 4 and 3 out of the 14 treatments in the situations with and without crop residue application, respectively. Absolute values of *M*, as well as of LOFIT and RMSE, for the situations without crop residue application were higher than those with crop residue application.

In the situations without crop residue application, SOC in the layer of 0–20 cm, changed from approximately 6 Mg C ha^{-1} to approximately 4 Mg C ha^{-1}.

Reason for underestimation of simulated changes in SOC

As mentioned above, Roth-C simulated C dynamics in the Sahel reasonably well. However, simulated values were significantly lower than observed, particularly in the situations without crop residue application. Assuming that model structure has no problem, this underestimation seemed to be due to the incorrect setup of model parameters. The underestimation of SOC-contents in the model might be attributed to underestimation of annual C inputs or to an incorrect setting of the DPM:RPM ratio for the plant material. Therefore, a sensitivity analysis of SOC dynamics simulation for these two parameters was carried out.

Hence, we used two different annual C inputs (actual value +0.3 Mg C ha^{-1} and actual value +0.6 Mg C ha^{-1}) and three DPM:RPM ratios (1.44 (DPM = 59%, RPM = 41%), 0.67 (DPM = 40%, RPM = 60%), and 3.35 (DPM = 77%, RPM = 23%)) for the Control and F plots in Site 1, where high positive *M* values were observed. The ratios of 1.44 and 0.67 are recommended by Roth-C for most crops and grasses and for unimproved grassland and scrub, respectively. The ratio of 3.35 was tested by Ayanaba and Jenkinson (1990), and resulted in good agreement between predicted and observed SOC changes in Nigeria.

The simulations with the three different DPM:RPM ratios showed almost no differences (Fig. 5), whereas those using different annual C inputs showed a clear positive response in terms of simulated SOC contents. Hence, the DPM:RPM ratio has no strong effect on simulated SOC-dynamics in the SZ, but annual C inputs do. Consequently, the underestimation in this experiment might be considered to be an error caused by an undervalued C input. However, the annual C inputs that were used in the model calculations were actual values that carefully analyzed in each

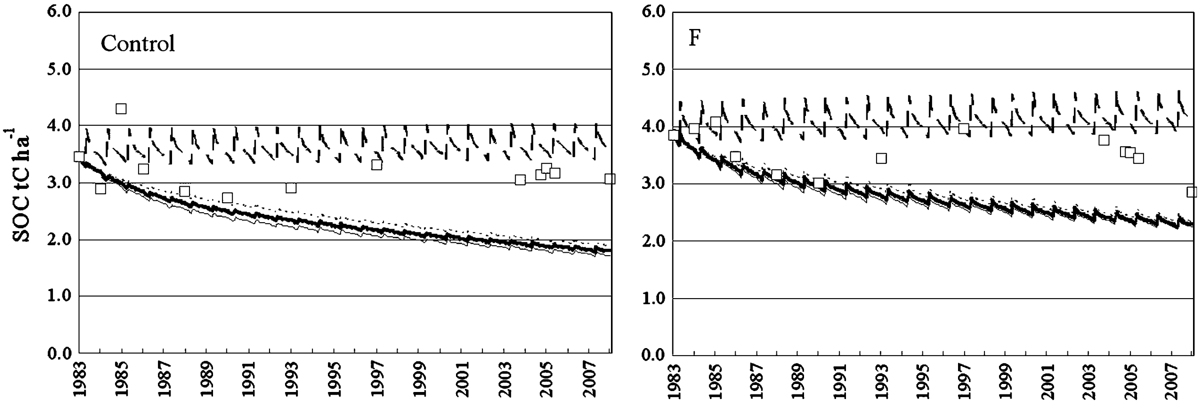

Fig. 5 Sensitivity analysis of different DPM:RPM ratios and of different amounts of C input in long-term experiment on Control and Fertilizer plots in Site 1. The *five lines* indicate simulation scenarios with a default DPM:RPM ratio (1.44) and observed C input (*thick black line*), with a DPM:RPM ratio of 3.35 and default C input (*thin line*), with a DPM:RPM ratio of 0.67 and default C input (*thin dotted line*), with a default DPM:RPM ratio of 1.44 and (0.3 Mg C ha^{-1})-added C input (*grayish thick dotted line*), and with a default DPM:RPM ratio of 1.44 and (0.6 Mg C ha^{-1})-added C input (*spaced thin line*), respectively. Further, the boxes indicate the observed SOC values

year, so it is difficult to consider that there are errors of inputted C values. And also this underestimation was conspicuous in the plot in the case without crop residue application. If there were serious errors in C input estimation, this model underestimation seemed to become prominence especially in the case with crop residue application, because of the high variability in millet yields. In addition, the model estimations in the (actual value +0.3 Mg C ha^{-1}) case showed fairly good agreement with the observed SOC values; however, the (0.3 Mg C ha^{-1})-added annual C input values were unrealistically high in the sensitivity analysis. Millet cultivation in the Control and F plots was carried out without crop residue application, thus, the main part of the annual C input was belowground biomass. As shown in Table 1, the determined annual C input (belowground biomass) values were 0.07–0.17 Mg C ha^{-1}. The (0.3 Mg C ha^{-1})-added input seems unrealistically high. Moreover, if there was an error in the calculation of the belowground biomass, the estimation in the other plots should also may the underestimation.

Therefore, this underestimation may be considered the result of some other factor. For example, Geiger et al. (1992) showed that the benefits of crop residue application were due to protection against wind erosion and changes in soil surface conditions, particularly in clay contents. This change in surface soil condition with wind erosion may affect the simulated SOC change.

Conclusions

The results of this study show that Roth-C generally satisfactorily simulates the SOC changes in a long-term trial in the SZ, semi-arid tropics, in various agricultural treatments, with and without crop residue applications. This fact means that Roth-C can estimate long-term SOC dynamics of several technical options that developed with short-term trials. All of agricultural techniques for farmers in SZ should be consider long-term SOC changes for the agricultural sustainability. On the discussion of sustainability, Roth-C can contribute to soil fertility aspect whereas the socio-economical survey will be required. As this paper mentioned, it is not necessarily the case that good technique for SOC management is acceptable for farmers because of socio-economical reasons.

Moreover the annual carbon requirement for SOC maintaining can be calculate if enough number of cases was estimated. And also analysis of regional carbon dynamics was made possible with using Roth-C model. It will contribute to show the sustainable development in SZ against global warming and other climatic changes.

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