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REGULAR ARTICLE

Modelling the dynamics of organic carbon in fertilization and tillage experiments in the North China Plain using the Rothamsted Carbon Model—initialization and calculation of C inputs

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Abstract Modelling of the carbon dynamics in arable soils is complex and the accuracy of the predictions is unknown before the model is applied to each specific site. Objectives were (i) to test the accuracy of predictions of the carbon dynamics using the Rothamsted Carbon (RothC) Model in a field trial in Quzhou, North China Plain, using different methods for initialization and estimation of carbon input into the soil and (ii) to test the applicability of the RothC model for plots with either conventional tillage (CT) or no-tillage (NT) systems. A field trial was conducted with applications of differing amounts of N (0, 112 or 187 kg N ha^{-1} $year^{-1}$), P (0, 75 or 150 kg P_2O_5 ha^{-1} $year^{-1}$) and wheat straw (0, 2.25 or 4.5 t DM ha^{-1} $year^{-1}$) in differing combinations with either CT or NT for 18 years. CT and NT affected stocks of soil organic carbon (SOC) similarly. Carbon inputs from crops were either estimated from published regression functions that relate C inputs to crop yield including rhizodeposition (models 1 and 2) or published root:aboveground biomass ratios (model 3). Model 1, which was not calibrated to the site conditions, was successful in predicting the carbon dynamics in seven out of nine treatments (model efficiencies EF ranged from 0.28 to 0.87), whereas for two treatments, EF (−0.35 and−2.3) indicated an unsuccessful prediction. The prediction of the C dynamics in NT experiments using model 1 was generally successful, but this may have been due to the fact that NT did not have a specific effect on SOC stocks for this trial. Model 2, which was the same as model 1 except for an optimization of the stock of inert organic matter using one treatment, predicted SOC stocks in the remaining eight treatments overall better than model 1. Model 3 was less successful than models 1 and 2 in all treatments ($-19 \leq EF \leq 0.56$). The results indicate that the RothC model may successfully predict C dynamics—for the site studied even without prior calibration as in model 1—, but care should be taken in choosing an appropriate approach for estimating C inputs into the soil.

Keywords Soil organic matter turnover · Modelling · Rothamsted Carbon Model · Conventional tillage · No-tillage · Winter wheat · Summer maize · North China Plain

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Introduction

Models which include the dynamics of soil organic carbon (SOC) may be useful for the prognosis of carbon sequestration in soils depending on management (e.g., fertilization, tillage, crop rotation; Balesdent 1996; Ludwig et al. 2007; Dendoncker et al. 2008) or other external factors (e.g., climate change, Falloon et al. 2007). They may improve our understanding of carbon turnover processes in soil (Malamoud et al. 2009) and they may be important components in other models such as those of crop growth (Franko et al. 1997; Gabrielle et al. 2002).

An important question for most applications of SOC models is whether the model can merely describe the data (e.g., after adjusting a stubble retention factor, Liu et al. 2009, or C inputs, Smith et al. 1997) or whether independent predictions are possible. In cases where model adjustments are required, it is advisable to split the data set for use in a calibration and validation procedure (Ludwig et al. 2007; Herbst et al. 2008), a common procedure in modelling. Overall, it is generally accepted that models must be properly validated (Addiscott 1993).

Estimated C input into the soil is of great quantitative importance for the model output of SOC models. Unfortunately, there is no general agreement as to which approach should be used for the estimation. For use in the Rothamsted Carbon (RothC) Model, some studies used optimized C inputs (Smith et al. 1997; Guo et al. 2007), others used simple ratios of belowground C to aboveground C (Skjemstad et al. 2004; Ludwig et al. 2005) and, only rarely, others have used regression functions that relate C inputs to crop yield (Ludwig et al. 2007). This issue of how to estimate C input has not received sufficient attention even though estimates of C input may largely depend on the approach used.

The RothC model has only rarely been applied to Chinese sites. Yang et al. (2003) calibrated the RothC model for a simulation of SOC changes in Chinese black soils under maize monoculture with different fertilizer treatments. SOC dynamics of the NPK treatment were described by using the equation by Falloon et al. (1998) for the stock of inert organic matter (IOM) and by adjusting the C inputs. For the other fertilizer treatments, higher (smaller) C inputs were assumed proportional to the increased (decreased) yields. The agreement between modelled and measured values varied between good (NPK + manure treatment) and unsatisfactory (NPK treatment). Guo et al. (2007) applied the RothC model to several long-term experiments in northern China, and it accurately simulated the changes in SOC across a wide area of northern China. However, C inputs were optimized in this study. Overall, there is not yet sufficient information how accurately the RothC model can predict SOC stocks in Chinese soils depending on the approach used for the estimation of C inputs.

The replacement of conventional tillage (CT) by reduced or no-tillage (NT) may favour soil carbon sequestration (Paustian et al. 2000; Jacobs et al. 2009) and has also been reviewed in the context of energy saving, sustainable fertility and reducing the degradation of arable soils (Ahl et al. 1998; Kushwaha et al. 2001). SOC dynamics under different tillage practices have only been modelled in few studies (Liu et al. 2009). Generally, it can be assumed that prediction accuracy may be less for NT soils than CT soils, since many SOC models, including the RothC model, assume spatial homogeneity. However, prediction accuracy for CT and NT soils has not been investigated in sufficient detail.

Objectives were (i) to test the accuracy of predictions of the carbon dynamics using the RothC model in a field trial in Quzhou, North China Plain, using different methods for initialization and estimation of carbon input into the soil and (ii) to test the applicability of the RothC model for plots with either CT or NT systems.

Materials and methods

Study site

The study was conducted in Quzhou County, in the middle of the North China Plain. The county is situated at latitudes between 36°35′43″ and 36°57′56″, and longitudes between 114°50′22″ and 115°13′27″. The total area is about 667 km^2 and the altitude is 39.6 m above sea level. The county has a continental monsoonal climate. The average annual air temperature is 13.3°C. The precipitation (mean values from 1983 to 2001) totals 482 mm per year, and 60% of the precipitation occurs from July to September. Potential evaporation (mean values from 1983 to 2003) calculated using the Penman Monteith approach is 1109 mm per year. Groundwater levels vary between 0.4 to 1.38 m yearly (Shi et al. 1986). In the county, the typical crop rotations are wheat-maize, wheat-soybean and wheat-cotton; and irrigation relies mainly on groundwater.

The soil is an Aquic Cambisol which has developed on alluvial plain. The texture consists of 10 % sand, 78 % silt and 12 % clay. The depth of the Ap horizon is 20 cm. In 1984, before the start of the field trial, content of C in the Ap horizon was 7 g kg^{-1} and content of N was 0.37 g kg^{-1}. pH in soil:water (1:2.5) extracts is alkalinic with 7.8. Bulk density of the Ap horizon is 1.35 g cm^{-3}.

Previous landuse before the field trial was wasteland because of serious saline-alkalinization due to non-sustainable agriculture. Scientists from the Beijing Agricultural University started to improve soil fertility in 1975 and winter wheat and summer maize rotation was introduced. Yields were low until the beginning of the fertilization trial described below.

The field trial initiated in 1984 consisted of nine treatments on plots with areas of 33 m^2 per plot. Each of the nine treatments was replicated three times, resulting in a total of 27 plots. Six treatments consisted of CT down to 20 cm depth, the other three were NT treatments. The nine fertilization treatments consisted of different applications of inorganic N (nil: N_0, 112 kg urea-N (ha year)$^{-1}$: N_1 and 187 kg urea-N (ha year)$^{-1}$: N_2), inorganic P (nil: P_0, 75 kg P_2O_5 (ha year)$^{-1}$: P_1 and 150 kg P_2O_5 (ha year)$^{-1}$: P_2) and straw (nil: $straw_0$, 2.25 t DM (ha year)$^{-1}$ which equaled 1.01 t C (ha year)$^{-1}$: $straw_1$ and 4.5 t DM (ha year)$^{-1}$ which equaled 2.03 t C (ha year)$^{-1}$: $straw_2$) in different combinations. Table 1 gives the different combinations used in the six treatments with CT and in the three treatments with NT. Straw was removed from the fields and straw from winter wheat was applied early June each year after harvest at a rate described above in the treatments with moderate and large straw additions (Table 1). Plots of all treatments were irrigated with 570 mm water per year and the irrigation was 60 mm per month (June), 80 mm (July, September and December) and 90 mm (March, April and May). No irrigation was carried out in the other months.

Table 1 Treatments in the North China Plain experiment

Treatment number	Treatment
1 – CT-$N_0P_0straw_0$	conventional tillage, no fertilization
2 – CT-$N_1P_1straw_1$	conventional tillage, application of 112 kg urea-N (ha year)$^{-1}$, 75 kg P_2O_5 (ha year)$^{-1}$ and 2.25 t straw (DM) (ha year)$^{-1}$
3 – CT-$N_2P_2straw_2$	conventional tillage, application of 187 kg urea-N (ha year)$^{-1}$, 150 kg P_2O_5 (ha year)$^{-1}$ and 4.5 t straw (DM) (ha year)$^{-1}$
4 – CT-$N_0P_1straw_2$	Conventional tillage, application of 75 kg P_2O_5 (ha year)$^{-1}$ and 4.5 t straw (DM) (ha year)$^{-1}$
5 – CT-$N_1P_2straw_0$	conventional tillage, application of 112 kg urea-N (ha year)$^{-1}$ and 150 kg P_2O_5 (ha year)$^{-1}$
6 – CT-$N_2P_0straw_1$	conventional tillage, application of 187 kg urea-N (ha year)$^{-1}$ and 2.25 t straw (DM) (ha year)$^{-1}$
7 – NT-$N_0P_2straw_1$	no-tillage, application of 150 kg P_2O_5 (ha year)$^{-1}$ and 2.25 t straw (DM) (ha year)$^{-1}$
8 – NT-$N_1P_0straw_2$	no-tillage, application of 112 kg urea-N (ha year)$^{-1}$ and 4.5 t straw (DM) (ha year)$^{-1}$
9 – NT-$N_2P_1straw_0$	no-tillage, application of 187 kg urea-N (ha year)$^{-1}$ and 75 kg P_2O_5 (ha year)$^{-1}$

Yields, soil analysis and statistics

Grain yields of the wheat-maize rotation were recorded in the years 1991, 1993 to 1995, 1998, 2001 and 2003 for winter wheat and summer maize for the nine treatments. Grain yields did not show a consistent temporal trend and mean values and standard errors for the treatments are shown in Table 2.

Soil samples were taken from the 0–20 cm depth from each plot and mean values of SOC stocks (n=3) were determined in the years 1984, 1987, 1990, 1991, 1993, 1996, 1998, 2000, 2001 and 2002 (Fig. 1). Standard errors were calculated for all years but were only kept by the research station and thus available to us for the years 1987, 1990 and 2002 (Fig. 1), since the original focus of the study was grain yields.

Contents of soil total nitrogen were determined by the Kjeldahl method. Carbon contents were determined using the potassium dichromate-wet combustion method. For this method, an external heating (170–180°C for 5 min) using oil baths was applied and a correction factor of 1.1 was used (Bao 2000).

Bulk density was determined by the cutting ring method (Liu 1996). We did not measure the temporal changes of the bulk densities, but the uncertainty may be small. Zhang et al. (2009) reported for soils of the Beijing area that soil bulk density after 8 years was 0.8–1.5% lower in sub-soiling tillage and NT treatments than in CT at both sites.

The soil particle size composition was analyzed with the pipette method (Gee and Bauder 1986).

Table 2 Grain yields of winter wheat and summer maize (dry matter including 14% water content) for the nine treatments of the North China Plain trial (means and standard errors)

Treatment number	Winter wheat (t DM ha^{-1})	Summer maize (t DM ha^{-1})
1 – CT-N_0P_0straw$_0$	1.23 (0.19)	2.67 (0.39)
2 – CT-N_1P_1straw$_1$	4.68 (0.48)	7.04 (0.38)
3 – CT-N_2P_2straw$_2$	5.06 (0.39)	7.90 (0.44)
4 – CT-N_0P_1straw$_2$	1.67 (0.25)	3.09 (0.33)
5 – CT-N_1P_2straw$_0$	4.77 (0.41)	7.07 (0.37)
6 – CT-N_2P_0straw$_1$	1.17 (0.16)	4.03 (0.28)
7 – NT-N_0P_2straw$_1$	1.27 (0.21)	2.72 (0.28)
8 – NT-N_1P_0straw$_2$	1.44 (0.16)	5.39 (0.27)
9 – NT-N_2P_1straw$_0$	3.40 (0.49)	7.19 (0.66)

Mean values were calculated from available data of seven years for each of the crops during the treatment period

The performance of the model predictions of the C dynamics was evaluated by calculation of the root mean square error RMSE, model efficiency EF and relative error E as defined in Smith et al. (1997):

$$\mathrm{RMSE} = \frac{100}{\overline{O}}\sqrt{\sum_{i=1}^{n}(P_i - O_i)^2 \Big/ n}, \tag{1}$$

$$\mathrm{EF} = \frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}, \tag{2}$$

$$E = \frac{100}{n}\sum_{i=1}^{n}(O_i - P_i)/O_i, \tag{3}$$

where O_i are the observed (measured) values, P_i are the predicted values, $\overline{O}$ is the mean of the observed (measured) data and n is the number of paired values. RMSE ranges from 0 to ∞, EF from −∞ to 1 and E from −∞ to ∞. For an ideal fit, RMSE and E equal zero and EF equals 1.

We define predictions of SOC stocks with model efficiencies EF≥0.7 as good predictions, predictions in the range 0 < EF < 0.7 as satisfactory ones and predictions with EF≤0 as unsatisfactory.

Modelling the C dynamics with the Rothamsted Carbon Model

We used the RothC model (ROTHC26-3) (Jenkinson and Rayner 1977; Coleman and Jenkinson 1999) which includes the following pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (Cmic), humified organic matter (HUM) and IOM to calculate the C dynamics in the nine treatments from the beginning of 1985 to the end of 2002, where the last measurement of C stocks was carried out. The ROTHC26-3 version had been tested by Smith et al. (1997). The decay of the pools DPM, RPM, Cmic and HUM follows first-order kinetics, and the decomposition rate constants (year^{-1}) are 10.0 (DPM), 0.3 (RPM), 0.66 (Cmic) and 0.02 (HUM) (Coleman and Jenkinson 1999). The data requirements are given in Table 3. Evapotranspiration was calculated using the equation by Penman Monteith and open pan evaporation was then obtained by dividing the evapotranspiration by 0.75 (Coleman and Jenkinson 1999).

Ideally, for an initialization of the RothC model, ^{14}C measurements preferably from pre- and post-bomb samples should be used for the quantification of IOM (Rethemeyer et al. 2007). Such a quantification has often resulted in plausible results (but not always as reported for Bad Lauchstädt by Ludwig et al. (2007)). However, no ^{14}C data were available for this site. We tested three versions of ROTHC26-3 to calculate the C dynamics. In all the versions, we assumed that a steady state existed in the end of 1984. The parameterization was as follows.

Model version 1 (using the Falloon equation and the carbon input by roots and harvest residues from published functions that relate C inputs to crop yield including rhizodeposition)

No calibration was required for the predictions from the beginning of 1985 onwards, except for the initialization in 1984.

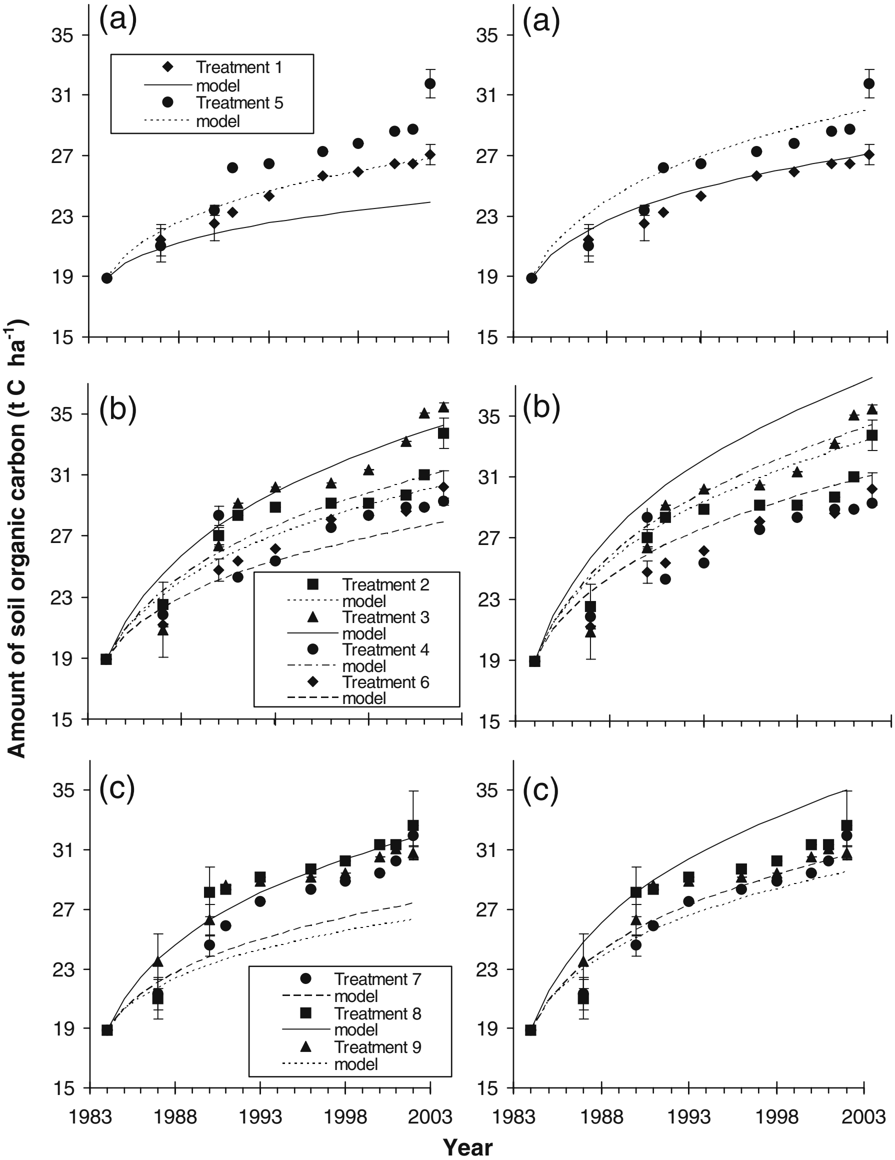

Fig. 1 Amounts of soil organic carbon for the nine treatments. The symbols show the mean measured quantities for 0–20 cm (n=3) and the solid lines show the model results for model 1 (left) and model 2 (right). Subfigure **a** shows the results for the CT plots without straw additions, **b** for the CT plots with straw additions and **c** shows the results for the NT plots. Standard errors are shown for the years 1987, 1990 and 2002 (one outlier in treatment 4 at 2002 was removed)

Initialization the stock of IOM was calculated from the total stock of SOC using the equation by Falloon et al. (1998) and the value obtained was 1.39 t C ha^{-1} (Table 5). Initial distribution of the other four pools in 1984 was obtained by optimizing the carbon input into the soil by wheat and maize (1.73 t C ha^{-1} year^{-1}) until 1984 by assuming steady state conditions and by matching the initial SOC stock of 18.9 t C ha^{-1} (Table 5).

Prediction from the beginning of 1985 onwards, C input was calculated from the aboveground yields of grain (Table 2) using the equation suggested by Franko (1997) and the constants given below and additionally considering the input by rhizodeposition by multiplying the inputs by 1.5 as suggested by Ludwig et al. (2007):

$$C_{input} = (K_{RHR} + F_{RHR} \times \text{yield}) \times 1.5, \qquad (4)$$

C_{input} is the C input by root and harvest residues (excluding straw) into the soil, yield refers to grain yield (in dt DM (including 14% water content) per ha). K_{RHR} and F_{RHR} are crop specific constants and the values are K_{RHR}=4.0 dt C ha^{-1} and F_{RHR}=0.080 dt C (dt DM)$^{-1}$ for winter wheat and K_{RHR}=13.5 dt

Table 3 Data requirements for the Rothamsted Carbon Model

Variable	Data
Average monthly mean air temperature (°C[a])	−2.3 (J), 1.2 (F), 7.0 (M), 14.7 (A), 20.0 (M), 25.6 (J), 27.1, (J), 25.4 (A), 20.7 (S), 14.5 (O), 6.0 (N),−0.1 (D)
Monthly precipitation plus irrigation (mm[a])	5 (J), 5 (F), 105 (M), 111 (A), 133 (M), 110 (J), 209 (J), 114 (A), 127 (S), 35 (O), 13 (N), 83 (D)
Monthly open pan evaporation (mm[a])	38 (J), 58 (F), 107 (M), 155 (A), 192 (M), 236 (J), 203 (J), 173 (A), 132 (S), 96 (O), 53 (N), 35 (D)
Soil depth (cm)	20
Clay content of the soil (%)	12
DPM/RPM ratio for the crops	1.44[b]
Soil cover	Winter wheat: covered from October till June. Maize: covered from July till September
Monthly input of plant residues	Unknown, obtained as described in Table 4 and in the text
Amount of inert organic matter	Models 1 and 3: 1.39 t C ha^{-1}, calculated from the stock of SOC using the equation by Falloon et al. (1998)
	Model 2: 10.2 t C ha^{-1}, optimized as described in the text

[a] The weather data were taken from a nearby station. Irrigation data was included

[b] The value suggested by Coleman and Jenkinson (1999) was used

C ha^{-1} and F_{RHR}=0.060 dt C (dt DM)$^{-1}$ for grain maize (Franko 1997).

Calculated C inputs by root and harvest residues ranged from 3.0 to 4.0 t C ha^{-1} $year^{-1}$ in the nine treatments (Table 4). Additionally, the measured straw inputs (nil, 1.0 or 2.0 t C ha^{-1} $year^{-1}$) were included in the model, resulting in total C inputs in the range from 3.0 to 6.0 t C ha^{-1} $year^{-1}$ (Table 4).

Model version 2 (use of treatment 1 for a calibration and carbon input by roots and harvest residues was calculated from published functions that relate C inputs to crop yield including rhizodeposition)

Model version 2 was the same as model 1, except that the stock of IOM and the initial distribution of the other four pools were calculated in a calibration procedure.

Initialization and calibration stock of IOM and carbon inputs until 1984 (assumption of steady state conditions) were optimized iteratively in order to match the measured C stock in 1984 and by using Eq. 4 from the beginning of 1985 onwards to also match the measured C stock in treatment 1 in 2002. The optimized data were then: stock of IOM=10.2 t C ha^{-1} and annual C input until 1984=0.86 t C ha^{-1} $year^{-1}$ (Table 5).

Prediction predictions for the other treatments 2–9 were carried out by using Eq. 4 and also the measured straw inputs as described for model version 1.

Model version 3 (using the Falloon equation and the carbon inputs by roots and harvest residues estimated from published root:aboveground biomass ratios)

No calibration was required for the predictions from the beginning of 1985 onwards, except for the initialization in 1984.

Initialization initial conditions (stocks of IOM and the other four pools) were obtained as described for model version 1 (Table 5).

Prediction from 1985 onwards, C input from wheat and maize was calculated as follows:

$$C_{input} = a \times yield/HI \times C\,content, \tag{5}$$

C_{input} is the C input by root and harvest residues into the soil, yield refers to the grain yield of winter

Table 4 C inputs in the models 1, 2 and 3 for the nine treatments

Treatment number	Model 1, 2 & 3	Models 1 & 2			Model 3		
	C input from straw	C input from wheat	C input from maize	Total C input	C input from wheat	C input from maize	Total C input
	(t C ha^{-1} $year^{-1}$)						
1 – CT-$N_0P_0straw_0$	0.00	0.75	2.27	3.01	0.44	0.48	0.92
2 – CT-$N_1P_1straw_1$	1.01	1.16	2.66	4.83	1.69	1.27	3.96
3 – CT-$N_2P_2straw_2$	2.03	1.21	2.74	5.97	1.82	1.42	5.27
4 – CT-$N_0P_1straw_2$	2.03	0.80	2.30	5.13	0.60	0.56	3.18
5 – CT-$N_1P_2straw_0$	0.00	1.17	2.66	3.83	1.72	1.27	2.99
6 – CT-$N_2P_0straw_1$	1.01	0.74	2.39	4.14	0.42	0.72	2.16
7 – NT-$N_0P_2straw_1$	1.01	0.75	2.27	4.03	0.46	0.49	1.96
8 – NT-$N_1P_0straw_2$	2.03	0.77	2.51	5.31	0.52	0.97	3.51
9 – NT-$N_2P_1straw_0$	0.00	1.01	2.67	3.68	1.22	1.29	2.52

wheat or summer maize, HI is the harvest index (grain yield / total aboveground biomass), which we estimated as 0.5 (which equals a grain:straw ratio of 1), and C content is the C content of the aboveground biomass (straw plus grain), which we estimated as 45%. The factor a for winter wheat was set to 0.4 as suggested by Skjemstad et al. (2004) and it was set to 0.2 for summer maize as suggested by Balesdent and Balabane (1992) and Ludwig et al. (2005). As we wished to test the applicability of the approaches used as in the studies by Skjemstad et al. (2004) and Ludwig et al. (2005) we likewise did not consider rhizodeposition in model version 3.

The calculated C inputs by root and harvest residues were much smaller for those treatments where grain yields were small and ranged from 0.9 to 3.2 t C ha^{-1} $year^{-1}$ for all treatments. By additionally considering the measured straw inputs, total C inputs ranged from 0.9 to 5.3 t C ha^{-1} $year^{-1}$ (Table 4).

We additionally tried to create a model version 4 (not shown), where IOM and annual C inputs until 1984 were optimized, and the approaches which relate the C input to the root:aboveground biomass ratios (Eq. 5) were used from 1985 onwards. We aimed to match the SOC stocks in 1984 and in 2002 for the treatment 1 (CT-$N_0P_0straw_0$). However, it was not possible to match SOC stocks in 2002, even with the unrealistic assumption that all SOC in 1984 was assumed to be IOM. The estimated C inputs using Eq. 5 were too low.

Table 5 Initial conditions of the models in 1984

Parameter	Models 1 & 3	Model 2
C inputs until 1984 (t C ha^{-1} $year^{-1}$)	1.73	0.86
Stocks (t C / ha)		
DPM	0.32	0.19
RPM	2.95	1.48
Cmic	0.37	0.18
HUM	13.86	6.85
IOM	1.39	10.20
Total C stock	18.88	18.90

Results

Yields and carbon data

Grain yields of winter wheat were small for the nil fertilization treatment (12.3 dt DM ha^{-1}, Table 2). In all treatments, where either inorganic N or inorganic P was not applied, yields did not respond well: grain yields in the treatments without inorganic P (CT-$N_2P_0straw_1$, NT-$N_1P_0straw_2$) ranged from 11.7 to 14.4 dt DM ha^{-1}) and grain yields in the treatments without inorganic N (NT-$N_0P_2straw_1$, CT-$N_0P_1straw_2$) ranged from 12.7 to 16.7 dt DM ha^{-1} (Table 2). The combined application of inorganic N (at doses of 112 or 187 kg urea-N (ha year)$^{-1}$) and inorganic P (at doses of 75 or 150 kg P_2O_5 (ha year)$^{-1}$) with or without additional straw incorporation resulted in much greater yields in the range of 34.0 to 50.6 dt DM ha^{-1} (Table 2). Both winter wheat and summer maize gave highest yields in the treatment with largest additions of N, P and straw (CT-N_2P_2straw$_2$, Table 2). In contrast to winter wheat, summer maize showed a stronger response to N fertilization without P fertilization, the treatments NT-N_1P_0straw$_2$ and CT-N_2P_0straw$_1$ gave markedly larger yields than the treatments without addition of inorganic N (Table 2).

The fertilization trial covered a wide range of straw additions and grain yields (which resulted in a range of belowground yields). Thus we expected that the experiments would result in marked changes in SOC stocks after 18 years of the trial. In all treatments, including the nil fertilization treatment, where the stock increased by 8.2 t C ha^{-1}, stocks of SOC increased considerably during the 18 years (Fig. 1), indicating that management had improved from 1985 onwards. The largest increase occurred as expected in the treatment with largest additions of inorganic N and P and straw (SOC stock: 35.5 t C ha^{-1}), followed by the treatments with moderate additions of inorganic N and P and straw (SOC stock: 33.7 t C ha^{-1}, Fig. 1). Smallest increases occurred in the nil treatment (SOC stock: 27.1 t C ha^{-1}) and the treatment without inorganic N, moderate inorganic P and large straw additions (SOC stock: 29.3 t C ha^{-1}, Fig. 1). SOC stocks in NT treatment were in the same range as in the CT treatments, but spatial variability was largest for NT-N_1P_0straw$_2$ (Fig. 1).

The approach by Franko which relates C inputs to crop yield by additionally considering rhizodeposition (Eq. 4) and the measured straw inputs showed the same order of increasing annual C inputs for the CT treatments (Table 4) as the order of SOC stocks (Fig. 1). However, one exception was noted: for treatment CT-P_0N_1straw$_2$, estimated C inputs did result only in small increases of SOC stocks, probably because straw contributes less to the built up of SOC than root and harvest residues. The approaches which relate the C input to the root:aboveground biomass ratios (Eq. 5) had the same order of C inputs, but absolute values were much smaller (Table 4, Fig. 1). Model versions 1 and 2 (approach by Franko) and model version 3 (Eq. 5) were used to test the usefulness of these approaches for predicting SOC changes depending on yields and straw additions. The results are reported below.

Performance of the model version 1 (using the Falloon equation and the carbon input by roots and harvest residues from published functions that relate C inputs to crop yield including rhizodeposition)

Model version 1, which used the Falloon equation for the estimation of the stock of IOM and the Franko approach by additionally considering rhizodeposition (Eq. 4), predicted changes in SOC stocks well (EF≥ 0.7) in three CT treatments, satisfactorily (0 < model efficiencies EF<0.7) in two CT treatments, and unsatisfactorily in one CT treatment (Fig. 1, Table 6). This satisfactory to good performance in five out of six treatments was surprising, since no treatment was used for calibration, and it indicated that the RothC model may be useful for predictions of SOC stocks when information (measurements or estimates) on the grain yields are available.

For the NT treatments, the prediction of the C dynamics was successful in two treatments (EF=0.3 and 0.8), but large deviations between modelled and measured SOC stocks occurred in treatment 9 with EF=−2.3 (Fig. 1, Table 6).

No consistent relative error *E* between modelled and measured SOC stocks was present, *E* ranged from -5 to 14 t C ha^{-1} and largest relative errors *E* were noted for treatments 9, 1 and 7 (Table 6).

Performance of model version 2 (use of treatment 1 for a calibration and carbon input by roots and harvest residues was calculated from published functions that relate C inputs to crop yield including rhizodeposition)

Model version 2 included a calibration where the stock of IOM and the annual C inputs until 1984 were optimized using treatment 1. From the beginning of 1985 onwards, the approach by Franko (Eq. 4) was used as described for model version 1 above. The description of the SOC stocks in treatment 1 was good (EF=0.9, Table 6, Fig. 1). The accuracy of predictions in the remaining eight treatments was good for two CT and one NT treatments and

Table 6 Statistics describing the performance of the models 1 to 3 in the description (model 2, treatment 1) and prediction (models 1 and 3: all treatments, model 2: treatments 2–9) of organic C stocks (n=9 for each treatment)

Treatment number	Model 1			Model 2			Model 3		
	EF	RMSE	*E*	EF	RMSE	*E*	EF	RMSE	*E*
1 – CT-N_0P_0straw$_0$	−0.35	8.9	7.8	0.90	2.4	−2.0	−19	34	32
2 – CT-N_1P_1straw$_1$	0.66	5.8	3.8	0.63	6.1	−4.6	−1.3	15	14
3 – CT-N_2P_2straw$_2$	0.87	5.1	−2.2	0.47	10	−10	0.56	9.3	6.0
4 – CT-N_0P_1straw$_2$	0.37	7.1	−5.1	−2.0	15	−14	−3.0	18	16
5 – CT-N_1P_2straw$_0$	0.36	8.8	6.1	0.81	4.8	−3.0	−2.0	19	17
6 – CT-N_2P_0straw$_1$	0.73	5.1	3.5	0.67	5.6	−5.5	−7.0	28	26
7 – NT-N_0P_2straw$_1$	0.28	9.3	7.3	0.91	3.3	−1.4	−7.4	32	29
8 – NT-N_1P_0straw$_2$	0.84	4.4	0.61	0.39	8.6	−7.7	−2.5	21	19
9 – NT-N_2P_1straw$_0$	−2.3	14	14	0.44	6.0	5.4	−11	27	26

satisfactory for two CT and two NT treatments (Table 6, Fig. 1). Only SOC stocks in treatment 4 were overestimated considerably with EF < 0. Root mean square errors RMSE were similar to those of model version 1, but there was a consistent negative bias *E* and the plot of measured against modelled SOC stocks indicated a slight overestimation of most SOC stocks (Table 6, Fig. 2).

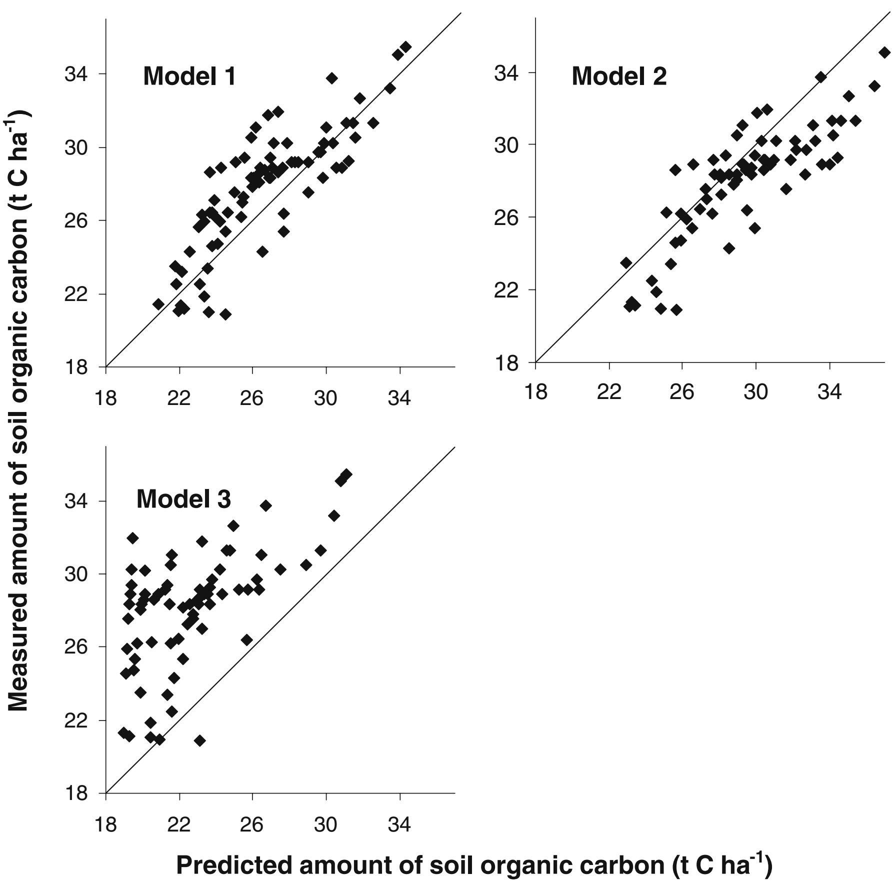

Fig. 2 Measured against modelled amounts of soil organic carbon for the models 1, 2 and 3. The lines indicate the 1:1 relation

Performance of model version 3 (using the Falloon equation and the carbon inputs by roots and harvest residues estimated from published root:aboveground biomass ratios)

Model version 3, which used the Falloon equation for the estimation of the stock of IOM and approaches which relate the C input to the root:aboveground biomass ratios (Eq. 5), was not useful for a prediction of the SOC dynamics: EF was <0 in all but one treatment (Table 6). The plotting of measured against modelled SOC stocks indicated a large underestimation of SOC stocks for almost all data points and the relative error E was marked (Fig. 2, Table 6).

Discussion

Yields and carbon data

Grain yields in treatments without fertilization were small for winter wheat and summer maize. Yields responded markedly to NP fertilization (winter wheat, summer maize) or N fertilization (summer maize). The yields for winter wheat (1.2 to 5.1 t DM ha^{-1}) and maize (2.7 to 7.9 t DM ha^{-1}) are in a similar range to those reported for a fertilization trial in Changping (northern China), where ranges of 2.1 to 5.4 t DM ha^{-1} and 3.1 to 5.9 t DM ha^{-1} were observed, respectively (Guo et al. 2007).

Stocks of SOC increased in all nine treatments, including the nil-fertilization treatment and increased with increasing grain yields (and thus aboveground yields) and straw additions. The increase of SOC stocks in nil-treatments is not common, other studies usually report no changes with time or even decreases (e.g., Ludwig et al. 2007; Guo et al. 2007); it indicates how severely the site was degraded due to the secondary alkalinization in the phase of non-sustainable agriculture before the improvement of soil fertility from 1975 onwards.

During the 18 years of the trial, the only marked difference between CT and NT was a greater spatial variability of SOC stocks in the NT plots; SOC stocks and grain yields did not show marked differences to those of CT plots. In his review, Alvarez (2005) reported for paired data from 161 sites with contrasting tillage systems that under conservation tillage (reduced tillage and NT), SOC content was on average 2.1 t ha^{-1} greater than under CT. From 10 years onwards, SOC tended to increase under conservation tillage, reaching a new equilibrium around 25–30 years, where few data points suggested an increase of around 12 t C ha^{-1}. However, the time to reach a new equilibrium (25 to 30 years) was longer than in our study. Moreover, some of the studies summarized in Alvarez (2005) reported decreases of SOC stocks in NT plots compared to CT plots.

Performance of the model versions

Model version 1 which used the Franko approach for the estimation of C inputs into the soil was useful for a prediction of SOC stocks (EF>0) in five out of six CT treatments and in two out of three NT treatments. However, since NT did not have a specific effect on SOC stocks for this trial, the successful prediction in the two out of three NT treatments may not be reproducible at other sites.

As reported previously for other sites, there is no clear indication under what conditions larger deviations between modelled and measured SOC stocks may be expected. For instance, predictions of SOC stocks in the long-term trial at Bad Lauchstädt were useful for all treatments (Ludwig et al. 2007), whereas for Rotthalmünster, stocks of C_4-derived SOC was overestimated 1.6fold after 24 years of continuous maize cultivation (Ludwig et al. 2005).

In general, sources of uncertainty are:

i. which approach should be used for the estimation of C inputs into the soil? The two approaches compared in our study had a maximum difference in the nil-fertilization treatment with low yields (2.1 t C ha^{-1} $year^{-1}$), but large differences were also present in the fertilization treatments (0.7–2.1 t C ha^{-1} $year^{-1}$, Table 4).
ii. how should the stocks of IOM be obtained? There are several possibilities, each with its own limitations, as discussed below. Moreover, the assumption of an IOM pool is valid only as an approximation.
iii. which approach should be used for the estimation of potential evapotranspiration? We used here the Penman Monteith equation which is assumed to be superior to the ones of Thornthwaite or Haude (Guo et al. 2007; Müller 1982). Different

approaches give different results (Müller 1982) and at present there is no standard set for the use in the RothC model.

iv. how reliable are the experimental C stocks? In our study, the spatial variability was small, except for one NT treatment, whereas in other studies, a large spatial variability (Guo et al. 2007) or changed management such as deepening of the ploughing zone (Ludwig et al. 2008) make it difficult to conclude the accuracy of predictions.

v. for which soil types and textures is the RothC model most useful? Ludwig et al. (2008) indicated the differences between the model structure of the RothC model and a conceptual model derived from a large number of experiments. The simplified model structure of the RothC model may result in large deviations between modelled and measured data for some soils, but it is not yet known which soils are less useful for SOC predictions.

vi. how accurate are the temperature and moisture corrections in the RothC model? The RothC model has been successfully applied to arable soils on all continents, but for arid conditions an improvement of the calculation of the rate modifying constants for moisture may be required (Lobe et al. 2005). Bauer et al. (2008) compared the moisture and temperature reduction functions of several SOC models and summarized that there is a great inconsistency in the approaches of temperature and moisture reduction functions for the calculation of the pool decomposition rates.

vii. how did climate change affect the SOC dynamics during the experimental period? For instance, Bellamy et al. (2005) reported that carbon was lost from soils across England and Wales over the survey period between 1978 and 2003 at a mean rate of 0.6% year^{-1} relative to the existing soil carbon content.

viii. to what extent was C mineralization stimulated by the N fertilization in the different treatments? For instance, Khan et al. (2007) emphasized the role of fertilizer N in promoting the decomposition of crop residues and soil organic matter for a number of numerous cropping experiments involving synthetic N fertilization in the USA Corn Belt and elsewhere.

ix. to what extent does the pool structure of the RothC model reflect the SOC dynamics in the field? For instance, Ludwig et al. (2008) compared the structure of the RothC model with the one of a conceptual model based on experimental findings and reported that for the intermediate and passive pools of the conceptual model, the RothC model has considerably less counter parts.

The comparison between the accuracy of predictions of model version 1 and 3 indicates that model version 3 was not useful for this data set (Table 6, Fig. 2). Thus, at least for this site, the approach by Franko (1997) plus the consideration of rhizodeposits as in Eq. 4 is more useful than the one in Eq. 5. Future studies should implement this approach or include at least the factor of 1.5 for rhizodeposition when Eq. 5 is used in order to reduce the uncertainty (i) given above.

Model version 2 gave better results than model version 1 for the calibration (treatment 1, Table 6, Figs. 1 and 2). This result is not surprising, since nine sources of uncertainty listed above exist. Any inaccuracy listed above may be counterbalanced in the calibration procedure—for instance, if the temperature and moisture reduction function result in an overestimation of decomposition (such as smaller modelled increase of SOC stocks than measured one as for some treatments in model 1) than an increase in the stock of IOM results in overall greater C stocks since less decomposable C is available for decay (as in model 2).

The predictions of the remaining eight treatments using model version 2 indicated an overall performance of 88 % good or satisfactory predictions compared to an overall performance of 78 % in model version 1 (Figs. 1 and 2, Table 6). This indicates that at present site-specific calibrations are still important and it suggests that studies which present solely model predictions without experimental data such as many DNDC model predictions (e.g. Tang et al. 2006) should be regarded as only very rough estimates.

Initialization of the RothC and other SOM models

Methods for SOM model initialization vary and have been reported to affect the accuracy of model output considerably (e.g., Leifeld et al. 2009). Suggested approaches include:

1. Estimating the amount of IOM from the total SOC content (Falloon et al. 1998), which is the cheapest, but serves only as an approximation.
2. Using ^{13}C and/or ^{14}C data for the initialisation (Falloon and Smith 2000; Rethemeyer et al. 2007). However, Ludwig et al. (2007) reported that for the long-term experiment in Bad Lauchstädt, Germany, initialization using ^{14}C data was not useful. Bruun and Jensen (2002) pointed out that besides the use of ^{13}C and/or ^{14}C data for the estimation of inert C also the distribution of SOM between the different pools should be in correspondence with the conditions at the beginning of the long-term experiments. Thus, the pre-experimental history should be known in as much detail as possible and equilibrium assumptions may not always be useful.
3. Estimating the amount of inert C by using the percentage of soil particles <6 µm or <20 µm or the pore size distribution (Puhlmann et al. 2006).
4. Determination of black C by UV photooxidation and NMR (Skjemstad et al. 2004).
5. Oxidation by H_2O_2 or $Na_2S_2O_8$ (Helfrich et al. 2007) or by NaOCl (Zimmermann et al. 2007).
6. Obtaining the amount of inert C by using one experimental treatment for the calibration.

In our study, we used the Falloon approach for model versions 1 and 3 (Table 5). This approach has the disadvantage that it is theoretically wrong: the inert (or passive) fraction cannot change as a consequence of management and climate and thus, the content of total C should not change either, if the Falloon equation had a strict validity. For model version 2, we used approach (6) (Table 5), which gave the best validation statistics (Table 6). This approach was also useful for the modelling of C stocks in the long-term fertilization experiment in Bad Lauchstädt. A disadvantage is that the development of C stocks in one treatment needs to be known before the model can be applied for predictive purposes.

A comparison of the initial results of model versions 1 (and 3) and 2 indicates that the differences in IOM are marked. The IOM pool size of 10.2 t ha^{-1} (54% of total C) in model 2 is large considering that initial total C was 18.9 t ha^{-1}, but the absolute value is in the upper range of IOM data obtained by using radiocarbon dating reported by Falloon et al. (1998).

In our model versions we used the assumption of steady state conditions in 1984. Since the decomposition rate constant of the HUM pool is very small (0.02 year^{-1}) and thus the half life of the HUM pool is 34.7 years (without the consideration of the rate modifying factors), at least several decades of constant conditions before the start of the trial in 1984 would be required for a good approximation of this assumption. For our trial, this assumption may hold only as rough approximation with the land management prior to the trial being either wasteland or non-sustainable with low yields and thus low carbon inputs.

Since an initialization of the RothC model starting with just the amount of IOM is not meaningful, the remaining options are to use experimental fractionation for an estimation of the pools (Skjemstad et al. 2004, Zimmermann et al. 2007), near infrared spectroscopy (Michel and Ludwig 2009, Thomsen et al. 2009) or the assumption of steady state conditions. The experimental fractionation is not yet generally established and several uncertainties have to be noted. For instance, the assignment of the residual fraction of a NaOCl oxidation of the fraction greater than 0.45 µm and smaller than 0.63 µm to the IOM pool has only been tested against results of the Falloon equation which is theoretically wrong (Zimmermann et al. 2007). The suggestion by Skjemstad et al. (2004) that IOM is represented by black C may not always hold true as discussed in Ludwig et al. (2008), and finally the usefulness of near infrared spectroscopy for the initialization of the RothC model has not yet been tested for a variety of sites.

In our study, the successful prediction of the SOC dynamics using model version 2 may be explained either (i) by the fact that SOC contents before the start of the trial were so small due to the non-sustainable management prior to the trial so that the distribution of C between the pools HUM, Cmic, DPM and RPM was of minor importance or (ii) by the possibility that inaccuracies in the distribution of C in these pools were counterbalanced by an inaccuracy in the estimation of the IOM pool, resulting overall in a successful calibration and prediction.

Conclusions

The study indicated that model predictions are largely affected by the approach used for the estimation of carbon inputs into the soil, either an estimation from published regression functions that relate C inputs to crop yield including rhizodeposition or from published root:aboveground biomass ratios. Future studies may focus on whether the approach by Franko (1997) for an estimation of C inputs into the soil by additionally considering rhizodeposition (by multiplying the estimate by 1.5) is generally superior to other approaches for use in the RothC model.

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