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Predictive modelling of C dynamics in the long-term fertilization experiment at Bad Lauchstädt with the Rothamsted Carbon Model

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Summary

Models are important for predicting how soil organic carbon alters with changing environment and management. We tested three different ways of parameterizing the Rothamsted Carbon Model in four treatments from the long-term static fertilization experiment at Bad Lauchstädt. Four bare fallow plots were also used to test different ways of parameterizing the model. Model version 1 used $\Delta^{14}C$ to estimate the amount of inert organic matter whereas in versions 2 and 3 a long-term bare fallow treatment was used to estimate this amount. In version 1, C inputs were optimized from the long-term data. In version 2, crop inputs were estimated from published functions that relate C inputs to crop yields. In version 3, C inputs (average or minimum data) were taken from actual measurements of crop and root residues. In both versions 2 and 3, rhizodeposition was included as additional input of 50% (winter wheat, spring barley) or 35% (potatoes, sugar beet) of the C input by crop and root residues. The performance of the three versions decreased in the order $3 > 2 \gg 1$. Model efficiency and root mean square error were 0.86 and 6.1 for version 3 and 0.81 and 7.0 for version 2. Overall, our results indicate the need for a long-term treatment for calibration. Setting total C inputs as a function of crop yield performed satisfactorily. Measurements of crop and root residues gave a good representation of total C inputs when carbon from rhizodeposition was included as additional input.

Introduction

Models of soil organic carbon are important for predicting carbon sequestration in soils under various kinds of management (e.g. crop rotation, ploughing depth, type and amount of fertilizer). Moreover, such models might improve our understanding of the underlying stabilization of C in soil (Balesdent, 1996; Ludwig *et al*., 2003, 2005). Finally, they can be important components in other models such as those of crop growth (Gabrielle *et al*., 2002) and global climate change (Stehfest, 2005).

Predictive modelling (use of independent measurements or estimates of the model parameters, e.g. C inputs) is required for the above-mentioned tasks. However, many modelling exercises have focused on an optimum description of data (use of adjustable data, e.g. optimized C inputs) (e.g. Smith *et al*., 1997) rather than independent prediction.

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The Rothamsted Carbon Model has been generally successfully applied to several agricultural soils under various climates (Smith *et al*., 1997), and only in a few studies have marked deviations from the experimental data been reported (Ludwig *et al*., 2005; Lobe *et al*., 2005). The model is fairly simple, but it appears to be sufficiently complex for simulation of most of the existing long-term plots (Smith *et al*., 1997).

Agricultural long-term experiments such as the static fertilization experiment in Bad Lauchstädt, Germany, are important for testing the usefulness of models of soil organic C. Rigorous testing of a model to evaluate its usefulness and limitations requires both a long experimental period and many experimental treatments. The Bad Lauchstädt trial has been used previously for testing the Rothamsted Carbon Model (Coleman *et al*., 1997; results are also summarized in Smith *et al*., 1997). That study, in which there were no long-term bare fallow plots and carbon data were available only from 1956 to 1995, emphasized an optimum description of the C data: inputs of C were optimized, and the amount of inert organic C in the model was arbitrarily set to 3 t C ha^{-1}.

In contrast to optimizing C inputs in the model, the use of existing experimental data of crop and harvest residues (Klimanek, 1987, 1997) in the models might be more appropriate. Moreover, Franko (1997) derived a yield-dependent function of C input into the soil from experimental data and included the function in the CANDY model. However, the efficacy for other models of soil organic C has not been tested so far.

With the above findings in mind, we set ourselves the following objectives: (i) to test the efficacy of a calibration using Δ^{14}C or long-term data for a long-term prediction of the C dynamics, and (ii) to compare different approaches for the determination of C input into the soil for predictive modelling.

Materials and methods

Study site

The static fertilizer experiment at Bad Lauchstädt (51°24′N, 11°53′E) was initiated in 1902. The site is 113 m above sea level. The mean annual precipitation and temperature are 483 mm and 8.8°C, respectively. The soil type is a Haplic Chernozem derived from loess with the following horizons: Ap (0–30 cm), Ah (30–40 cm), Ah/C (40–60 cm). On all experimental plots the texture is loamy with the following grain-size distribution in the Ap horizon: 11.2% sand, 67.8% silt, and 21.0% clay. No carbonate is present in the soil down to 40 cm. Mean pH is 6.6. Mean bulk density in the Ap horizons of the treatments 1, 3, 5 and 7 (described below) is 1.35 g cm^{-3}. Körschens *et al.* (1994) provide additional information on the site and on the various treatments.

Soil samples were taken irregularly from 1902 onwards from field 2 where sugar beet, spring barley, potatoes and winter wheat were grown in continuous rotation. Straw and leaves of sugar beet were removed from the fields. No intercrops were grown. Previous land use before 1902 was also agriculture, presumably for centuries. The following treatments were considered (Table 1).

Treatment 1: A continuous crop rotation established in 1907 with varying NPK fertilization and the addition of 30 t farmyard manure (FYM) from cattle per hectare (approximately 2.7 t C ha^{-1}) every 2 years.

Treatment 3: A continuous crop rotation established in 1907 with the addition of 2.7 t C ha^{-1} as farmyard manure from cattle every 2 years.

Treatment 5: A continuous crop rotation established in 1903 with varying NPK fertilization.

Treatment 7: A continuous crop rotation established in 1903 without any fertilization.

Treatments 2, 4, 6 and 8 were the same as the respective treatments 1, 3, 5 and 7 except that bare fallows (all without any fertilization) were established in 1956 and continued until 2003 (Table 1). Soil material was taken with an auger from each treatment and filled into cement rings (depth, 70 cm; diameter, 65 cm) adjacent to the fields. The bottom layer consisted of 40–60 cm soil, followed by a second layer of 20–40 cm soil. These two layers were then compacted manually. Finally, Ap material was filled in the upper 20 cm of the cement rings without compaction. Soil in the cement rings was kept bare (no weeds or surface algal films were visible) by monthly manual weeding. Every autumn, the upper 20 cm was mixed and turned with little augers to simulate tillage. Mean bulk density in the upper 20 cm measured in threefold replication for each of the four treatments in 2006 was 1.24 g cm^{-3}.

Soils of the different treatments (1, 3, 5, 7 and 2, 4, 6, 8) were compared on an equal mass basis, i.e. the C stocks in Figures 1

Table 1 Treatments in the Bad Lauchstädt experiment

Treatment number	Treatment and period
1	NPK and FYM fertilization (1907–2002)
2	NPK and FYM fertilization (1907–1955), bare fallow (1956–2003)
3	FYM fertilization (1907–2002)
4	FYM fertilization (1907–1955), bare fallow (1956–2003)
5	NPK fertilization (1903–2002)
6	NPK fertilization (1903–1955), bare fallow (1956–2003)
7	Unfertilized (1903–2002)
8	Unfertilized (1903–1955), bare fallow (1956–2003)

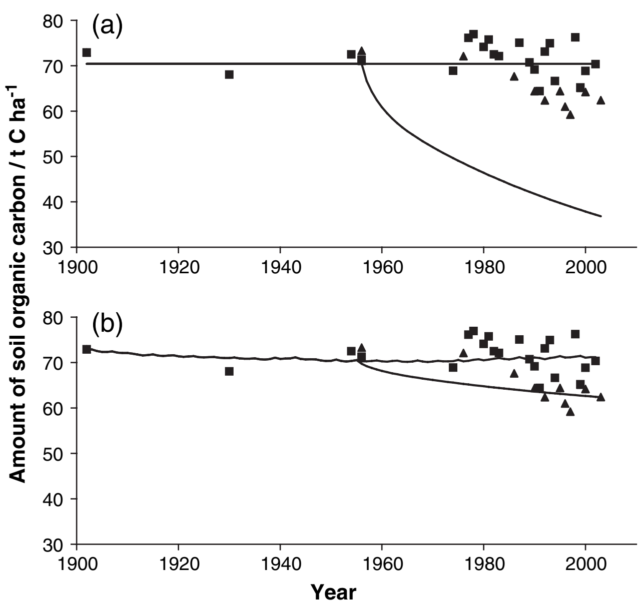

Figure 1 Amounts of soil organic carbon for the treatments 5 (NPK fertilization from 1902 until 2005) and 6 (NPK fertilization until 1955). The symbols show the measured quantities for 0–30 cm (treatment 5) and 0–32.7 cm (treatment 6 from 1956 onwards), and the solid lines show the model results for model versions 1 (a) and 2 (b).

and 2 refer to the 0–30 cm (treatments 1, 3, 5, 7) and 0–32.7 cm layer (treatments 2, 4, 6, 8 from 1956 onwards).

The N fertilization in treatments 1, 2 (until 1955), 5 and 6 (until 1955) depended on the crop and was varied according to the agricultural practices, which changed over the decades. For instance, until 1970, sugar beet received 60–120 kg N ha^{-1} year^{-1}, spring barley 20–40 kg N ha^{-1} year^{-1}, potatoes 20–60 kg N ha^{-1} year^{-1} and winter wheat 20–60 kg N ha^{-1} year^{-1}. From 1971 to 1977 more N was given. Since 1978, N fertilization varied according to the contents of inorganic N in the soils (Körschens *et al.*, 1994).

Yields, soil analysis and statistics

Yields and carbon content of off-take were recorded annually for the four crops (Table 2). Soil samples were taken with an auger from the 0–20 cm depths from the plots and from the cement rings. For each plot, 20 cores were taken and mixed. For each cement ring, five small cores were taken and mixed. Then the excess soil not needed for carbon analysis was returned to the cement ring. Samples were air-dried and sieved to pass 2 mm. Total carbon was determined by dry combustion, whereby CO_2 was detected by infrared adsorption (until 1995) or thermal conductivity (after 1995). The comparability of the two methods was tested before. The soil pH was determined in a 1-M KCl solution (soil:solution ratio 1:10). The soil's bulk density was determined on undisturbed soil cores.

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

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

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

$$\mathrm{CD} = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{\sum_{i=1}^{n}(P_i - \bar{O})^2}, \tag{3}$$

and

$$E = \frac{100}{n}\sum_{i=1}^{n}(O_i - P_i)/O_i, \tag{4}$$

where O_i are the observed (measured) values, P_i are the predicted values, $\bar{O}$ is the mean of the observed (measured)

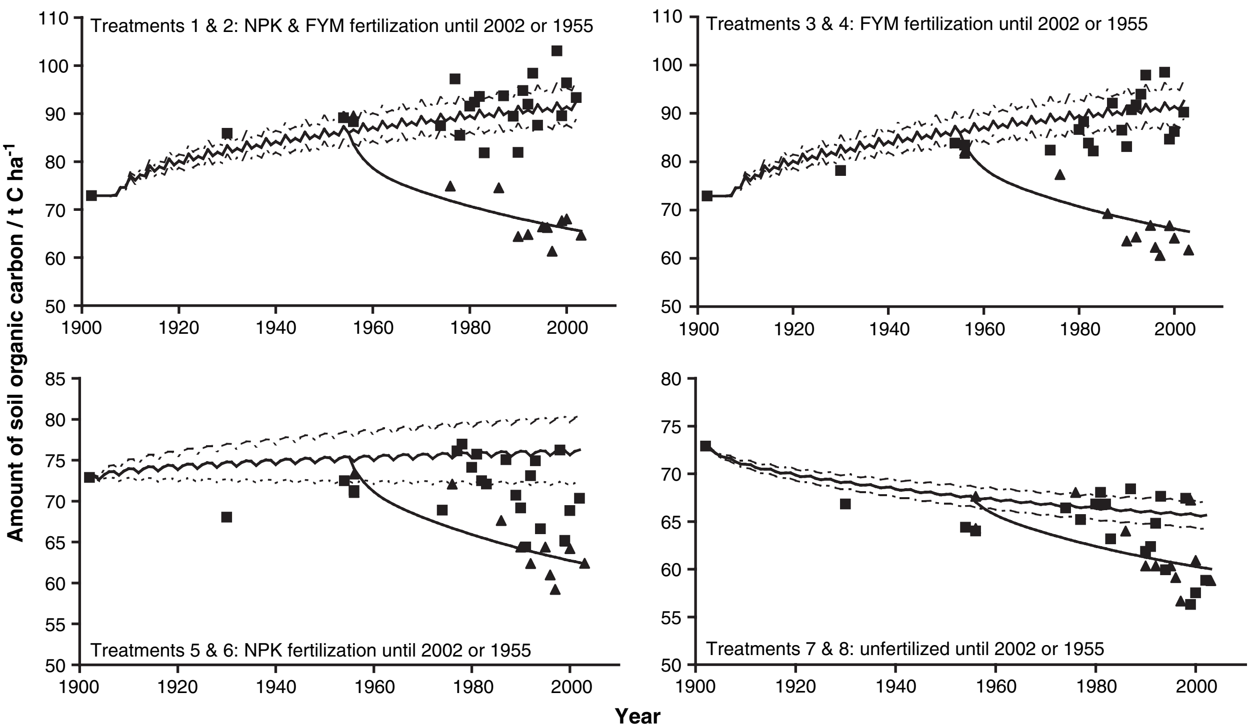

Figure 2 Amounts of soil organic carbon for the eight treatments. The symbols show the measured quantities for 0–30 cm (treatments 1, 3, 5 and 7) and 0–32.7 cm (treatments 2, 4, 6 and 8 from 1956 onwards), and the solid lines show the model results for model version 3. The dashed lines indicate the predictions with an assumed uncertainty of the C inputs of 25% in the treatments 1, 3, 5 and 7.

Table 2 Yields of the main products (fresh matter for sugar beet and potatoes) or grain (dry matter including 14% water content for barley and wheat) in the different treatments of the Bad Lauchstädt long-term trial (means and standard errors)

	Sugar beet /t fresh matter ha^{-1}	Spring barley /t dry matter ha^{-1}	Potatoes /t fresh matter ha^{-1}	Winter wheat /t dry matter ha^{-1}
Treatment 1 (FYM + NPK fertilization)				
1907–1960	43.0 (3.6)	3.65 (0.16)	27.3 (1.5)	3.93 (0.21)
1961–2002	54.5 (4.2)	5.26 (0.54)	37.6 (2.5)	6.53 (0.55)
Treatment 3 (FYM fertilization)				
1907–1960	38.7 (3.0)	3.05 (0.14)	19.3 (1.9)	3.80 (0.17)
1961–2002	48.7 (3.7)	4.49 (0.37)	31.5 (2.8)	5.98 (0.49)
Treatment 5 (NPK fertilization)				
1903–1960	39.0 (3.1)	3.14 (0.14)	20.8 (1.4)	3.77 (0.16)
1961–2002	52.6 (4.6)	4.61 (0.34)	32.5 (3.0)	6.71 (0.52)
Treatment 7 (unfertilized)				
1903–1960	22.1 (2.1)	1.70 (0.15)	8.29 (1.1)	2.56 (0.20)
1961–2002	22.2 (2.5)	2.39 (0.22)	9.91 (1.1)	3.52 (0.26)

data and n is the number of paired values. The RMSE and CD range from 0 to ∞, EF from $-\infty$ to 1 and E from $-\infty$ to ∞. For an ideal fit, RMSE and E equal zero and CD and EF equal 1. Note that CD as defined here is not the same as the more familiar coefficient of determination, R^2, of regression analysis.

AMS ^{14}C measurements

Soil samples from the Ap horizon of treatment 5 were taken in December 2005 in five-fold replication with an auger and bulked. Additionally, an archived sample (0–20 cm) from the same treatment sampled in 1956 was investigated. The samples were air-dried, sieved to pass 2 mm and acidified with 1% HCl which was evaporated by freeze-drying. Each sample was subsequently vacuum-dried and transferred into a precombusted quartz tube with 450 mg precombusted copper oxide and 150 mg silver wool. Each tube was evacuated and sealed in a flame, then combusted at 900°C for 4 hours, and the resulting CO_2 was subsequently collected in a cold trap with liquid nitrogen and reduced at 600°C with H_2 over about 2 mg of iron powder as catalyst. Each resulting mixture of carbon and iron was pressed into a pellet in a target holder for the accelerator mass spectrometer (AMS) as described by Nadeau *et al.* (1997, 1998).

The AMS measurements were made at Leibniz-Laboratory in Kiel (Germany), with a precision of about 0.3 pMC for modern, standard sized (1 mg C) samples (Nadeau *et al.*, 1998). The ^{14}C concentration was calculated from the measured $^{14}C/^{12}C$ ratio of the sample compared to the NIST – oxalic acid 2 standard (NIST, National Institute of Standards and Technology, Gaithersburg, MD), both corrected for isotopic fractionation by the simultaneously measured $^{13}C/^{12}C$ ratios. The $\Delta^{14}C$ contents were –281.5‰ (1956) and –188.5‰ (2005) and the apparent ^{14}C ages were 2645 (1956) and 1625 years BP (2005).

Modelling the C dynamics with the Rothamsted Carbon Model

We used the Rothamsted Carbon Model (ROTHC26-3) (Jenkinson & Rayner, 1977; Coleman & Jenkinson, 1999) which includes the following pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (Cmic), humified organic matter (HUM) and inert organic matter to calculate the C dynamics in the eight long-term treatments. Smith *et al.* (1997) had tested this version. The decay of the pools DPM, RPM, Cmic and HUM follows first-order kinetics, and the decomposition rate constants (year^{-1}) were set to 10.0 (DPM), 0.3 (RPM), 0.66 (Cmic) and 0.02 (HUM) as suggested by Coleman & Jenkinson (1999). The data requirements are given in Table 3.

We tested three versions of ROTHC26-3 to calculate the C dynamics. In all the versions, we assumed that a steady state existed in 1902. The parameterization was as follows.

Model version 1 (using ^{14}C data and optimized C inputs)

1 Calibration: The amount of inert organic C and the average C input into the soil were estimated by the routine 'Calculate plant inputs and IOM knowing total carbon and radiocarbon'. We assumed a soil cover from May until October, because it is in the range of the soil cover for the four crops (spring barley, 3 months; potatoes, 4 months; sugar beet, 6 months; winter wheat, 9 months). The final C stock of treatment 5 (70.3 t C ha^{-1}) as well as the $\Delta^{14}C$ value for the C sample in 2005 was used, and the optimized average C input into the soil was 3.3 t C ha^{-1} year^{-1} and amount of inert organic C was 17.9 t C ha^{-1}.
2 Prediction: We predicted the C dynamics in the long-term treatment 6. We ran the model described above until 1955 and then used nil input until 2003.

Table 3a Data requirements for the Rothamsted Carbon Model

Variable	Data
Average monthly mean air temperature/°C[a]	–0.2 (J), 0.5 (F), 4.1 (M), 8.2 (A), 13.1 (M), 16.2 (J), 18.0 (J), 17.4 (A), 13.9 (S), 9.1 (O), 4.1 (N), 1.0 (D)
Monthly precipitation/mm[a]	25.9 (J), 23.1 (F), 28.7 (M), 36.5 (A), 50.9 (M), 61.1 (J), 64.2 (J), 57.9 (A), 37.7 (S), 37.0 (O), 31.2 (N), 28.6 (D)
Monthly evaporation/mm[a]	12.9 (J), 17.5 (F), 33.6 (M), 54.2 (A), 84.7 (M), 95.2 (J), 98.3 (J), 85.6 (A), 54.9 (S), 33.0 (O), 16.4 (N), 11.9 (D)
Soil depth/cm	30 or 32.7 (treatments 2, 4, 6 and 8 from 1956 onwards)
Clay content of the soil/%	21
DPM/ RPM ratio for the crops	1.44[b]
Soil cover	Sugar beet: covered from May till October. Spring barley: covered from May till July Potato: covered from June till September. Winter wheat: covered from November till July
Monthly input of plant residues	Unknown, obtained as described in Table 3b and in the text
Amount of inert organic matter	Unknown, obtained as described in the model versions

[a]The weather data were taken from a nearby station. Values are means from 1902 until 2001.
[b]The value suggested by Coleman & Jenkinson (1999) was used.

The use of the ^{14}C data from 1956 according to the modelling procedure described above resulted in an optimized C input of 3.3 t C ha^{-1} year^{-1} and an amount of inert organic C of 18.9 t C ha^{-1}. Since these data were very similar to those of version 1, we considered no further variants of the model or any need to calculate mean inert organic C.

Model version 2, using long-term treatment 6 for the calibration and C inputs as function of the yields as suggested by Franko (1997)

1 C input as function of the yields: the C inputs from 1903 until 1955 (treatments 2, 4, 6, 8) or until 2002 (treatments 1, 3, 5, 7) were calculated as functions of the yields for each year and crop as described by Franko (1997):

$$C_{\text{input}} = K + \text{yield} \times F, \qquad (5)$$

where C_{input} is the C in the residues of the crop and its roots put into the soil in dt (decitonnes) C ha^{-1}, yield refers to the yield of fresh matter of the main product (sugar beet, potatoes) in dt fresh matter ha^{-1} or to the yield of dry matter of the grains (including 14% water content, spring barley, winter wheat) in dt dry matter ha^{-1}, and K and F are constants (see below). The values for K (in dt C ha^{-1}) are 4.0 (winter cereals), 3.1 (spring barley), 0.8 (potatoes) and 1.6 (sugar beet) and for F are 0.08 (winter cereals) and 0.078 dt C [dt dry matter ha^{-1}]$^{-1}$ (spring barley) and 0.016 (potatoes) and 0.008 dt C [dt fresh matter ha^{-1}]$^{-1}$ (sugar beet) (Franko, 1997).

The input calculation above does not take into account the C contributed by rhizodeposits (including exudates). As the Rothamsted Carbon Model requires information on all organic C inputs into the soil, this source of C had to be estimated. For winter wheat and spring barley, Kuzyakov & Domanski (2000) and Y. Kuzyakov (personal communication) estimated this input as 50% of the C input by crop and root residues, and for sugar beet and potatoes, Y. Kuzyakov estimated the input as 35% of the C input by crop and root residues. Thus, we multiplied the C inputs from Equation (5) by 1.5 (winter wheat, spring barley) or 1.35 (sugar beet, potatoes) for the use for the Rothamsted Carbon Model.

The constants in Equation (5) were obtained by a regression analysis of a large data set of experimental crop and root

Table 3b Mean C inputs for the model versions 2 and 3. For version 2, the range of C inputs in the years 1903 until 2002 are given in parentheses

Model versions and treatments	Sugar beet	Spring barley	Potatoes	Winter wheat
	C input/t C ha^{-1}			
Model version 2[a]				
Treatments 1, 2	0.73 (0.39–0.99)	0.97 (0.77–1.40)	0.80 (0.45–1.19)	1.21 (0.88–1.71)
Treatments 3, 4	0.68 (0.35–0.91)	0.89 (0.74–1.25)	0.65 (0.27–1.14)	1.18 (0.90–1.61)
Treatments 5, 6	0.70 (0.36–1.00)	0.90 (0.76–1.16)	0.67 (0.36–1.22)	1.21 (0.91–1.64)
Treatments 7, 8	0.46 (0.28–0.59)	0.70 (0.55–0.84)	0.30 (0.18–0.52)	0.96 (0.77–1.18)
Model version 3[b, c]				
Treatments 1–6[b]	0.91	1.22	1.85	2.43
Treatments 7, 8[c]	0.44	0.62	0.35	0.85

[a]Values were calculated using Equation (5) plus additional 50% (cereals) or 35% (sugar beet, potatoes) due to the C input by rhizodeposition.
[b, c]Values for crop and root residues from 5 (sugar beet), 11 (spring barley), 8 (potatoes) or 17 (winter wheat) experimental studies summarized by Klimanek (1987). The data are averages (b) and minimum values (c) plus additional 50% (cereals) or 35% (sugar beet, potatoes) due to the C input by rhizodeposition.

residues from agricultural long-term experiments in central Germany (Franko, 1997; U. Franko, personal communication). Also, the additional C inputs by rhizodeposits in version 2 were estimated independently. Thus, the model results for the various long-term treatments are predictions without the use of any adjustable parameters. Table 3b shows the range of calculated C inputs used in the model versions for each crop in the differing treatments. The mean values are also given in Table 3b, but were not used in the model.

2 Calibration: Two values were unknown, the amount of inert organic C and the annual C inputs until 1902. We estimated these two values using the Rothamsted Carbon Model by matching two conditions: (i) the initial stock of C was used as starting point (72.9 t C ha^{-1} in 1902) when a steady state was assumed, and the C inputs from 1903 until 1955 were calculated as described above, then from 1956 until 2003 there was input of no C. We assumed a soil cover from November until July for the land management until 1902, because in the 19th century and before, arable soils were generally covered for longer each year than in the 20th century. With just condition (i), infinite solutions for the amount of inert organic C and annual C inputs until 1902 exist. Condition (ii), matching the measured stock of C of the long-term treatment 6 in 2003 (62.4 t C ha^{-1}), gives a unique solution (Figure 1b). The values obtained to match these two stocks of C were 1.2 t C ha^{-1} year^{-1} for the annual C inputs until 1902 and 57.7 t C ha^{-1} for the amount of inert organic C.

3 Prediction: We predicted the C dynamics in the remaining seven long-term treatments by using the values obtained by the calibration and by calculating the C inputs from 1903 until 2002 as described above.

Model version 3, using long-term treatment 6 for the calibration and C inputs from the experimental data summarized by Klimanek (1987, 1997)

1 C input: The C inputs were taken from experimental data of crop and root residues in surface soils (0–30 cm) summarized by Klimanek (1987, 1997). For treatments 1–6 the average experimental values for the crop and root residues from Klimanek (1987, 1997) were used as C inputs, because yields differed only slightly between these treatments and were much larger than those of the unfertilized treatment (Table 2). For treatments 7 and 8, where the yields were exceptionally small (Table 2), the minimum experimental values were used in the model. The data summarized by Klimanek (1987, 1997) are measured values of crop and root residues in field experiments in Germany, Russia and the Czech Republic with various textures and soil types. Again, we considered the C input by rhizodeposits as 50% (winter wheat and spring barley) and 35% (sugar beet and potatoes) of the C input by crop and root residues (Table 3b).

2 Calibration: The calibration procedure was similar to the one of version 2: the amount of inert organic C and the annual C inputs until 1902 were estimated from the initial (72.9 t C ha^{-1} in 1902) and final C stocks (62.4 t C ha^{-1} in 2003) of the long-term treatment 6 and the C inputs from 1903 until 1955, as described above. We assumed a soil cover from November until July for the land management until 1902. The values obtained to match these C stocks (Figure 2) were 1.3 t C ha^{-1} year^{-1} for the annual C inputs until 1902 and 55.3 t inert organic C ha^{-1}.

3 Prediction: We predicted the C dynamics in the remaining seven long-term treatments by using the values obtained by the calibration and by calculating the C inputs from 1903 until 2002, as described above.

Results and discussion

Yields and carbon data

For all treatments and crops, yields of the main products (sugar beet, potatoes) or grain (barley, wheat) were less between 1903 and 1960 than they were from 1961 to 2002 (Table 2). We attribute the yield increase from 1961 onwards mainly to increased N additions in the NPK treatments, the use of varieties with larger yields and optimized use of growth promoters and pesticides (Körschens *et al*., 1994). Treatment 7 gave exceptionally small yields for all four crops. Treatments 3 and 5 gave very similar yields in each of the periods. The largest yields were generally achieved in treatment 1 for all crops (Table 2).

Stocks of soil organic C in the Ap horizons varied considerably, but trends were obvious: as expected, the addition of farmyard manure resulted in increased stocks of C in the soil. Besides this effect, increased additions of fertilizer (farmyard manure + NPK > farmyard manure, NPK > nil) resulted in increased yields (Table 2) and also increased stocks of C (Figure 2), presumably due mainly to an increased formation of biomass in the soil, since the straw of wheat and barley was removed. Mean values (1998–2002, standard errors are given in parentheses) of C stocks in t C ha^{-1} decreased in the order 95.6 (2.9) for treatment 1 > 89.9 (3.1) for treatment 3 $\gg$ 70.2 (2.3) for treatment 5 $\gg$ 60.0 (2.5) for treatment 7. This finding suggests that the yield-dependent estimate of C input (Franko, 1997) or the use of average (treatment 1, 3, 5) and minimum (treatment 7) experimental crop and root residue data (Klimanek, 1987, 1997) could be used as C inputs in models to predict C dynamics in soils (see below).

Performance of the model version 1 (optimizing C inputs and use of $\Delta^{14}C$ for the estimation of inert organic C)

Model version 1, which used optimized C inputs and where Δ^{14}C was used for the estimation of inert organic C, gave good calibration results for treatment 5 (Figure 1a). However, C stocks of treatment 6 were substantially underestimated (Figure 1a). Thus, version 1 was not useful for this site.

Performance of the model versions which used a long-term experiment for their calibration

Model version 2 (use of treatment 6 of the long-term experiment for the calibration and of the Franko equation for the C inputs) performed better than version 1 (Figure 1b). The model efficiency, EF, was 0.81 for the prediction of the seven treatments and indicated that version 2 described the measured data markedly better than the mean of the measurements (Table 4). However, the plot of measured against modelled values (Figure 3), which shows two clusters (1, treatments without FYM additions and all bare fallow plots; 2, treatments with FYM additions), indicates that for either of the two clusters, the model predicted almost constant C stocks, despite large observed changes. Nevertheless, there was a large temporal variability of measured C stocks. Thus, estimating C inputs from the yields, as suggested by Franko (1997), by additionally accounting for the C inputs by rhizodeposits gave satisfactory results.

An additional model version 2b, which was the same as version 2 except for the assumption of a smaller ratio of DPM to RPM of 1, gave only small increases in C stocks in the treatments (not shown). Uncertainties in the decomposability of the organic inputs (e.g. larger ratios than 1.44 because of a greater decomposability of the rhizodeposits or smaller ratios than 1.44 (version 2) or 1 (version 2b) because of a smaller decomposability of the crop residues) are of much less significance than the uncertainties in the amounts of inert organic C and in the amounts of C inputs.

Version 3 (use of treatment 6 of the long-term experiment for the calibration and of the experimental data of root and crop residues summarized by Klimanek (1987, 1997) for the estimation of the C inputs plus rhizodeposition) performed well in the prediction of all 7 treatments (Figures 2 and 3, Table 4). Of the model versions tested, it was the most efficient (EF = 0.86), had the smallest RMSE (6.07) and CD was close to 1 (Table 4). However, the relative error E of –2.31 indicated a bias in the total difference between predictions and measurements. An assumed uncertainty of the C inputs of 25% covered most of the experimental data (Figure 2). For treatment 1, the C stocks were generally underestimated, which accords with this treatment's having the largest yields (Table 2). However, the use of the maximum experimental data of root and crop residues (Klimanek, 1987, 1997) resulted in an overestimation of C stocks (not shown).

Table 4 Statistics describing the performance of versions 2 and 3 in the prediction of organic C stocks for the seven treatments ($n = 115$)

	Model versions	
	2	3
Root mean square error, RMSE	6.97	6.07
Model efficiency, EF	0.81	0.86
Coefficient of determination, CD	2.06	1.22
Relative error, E	0.22	–2.31

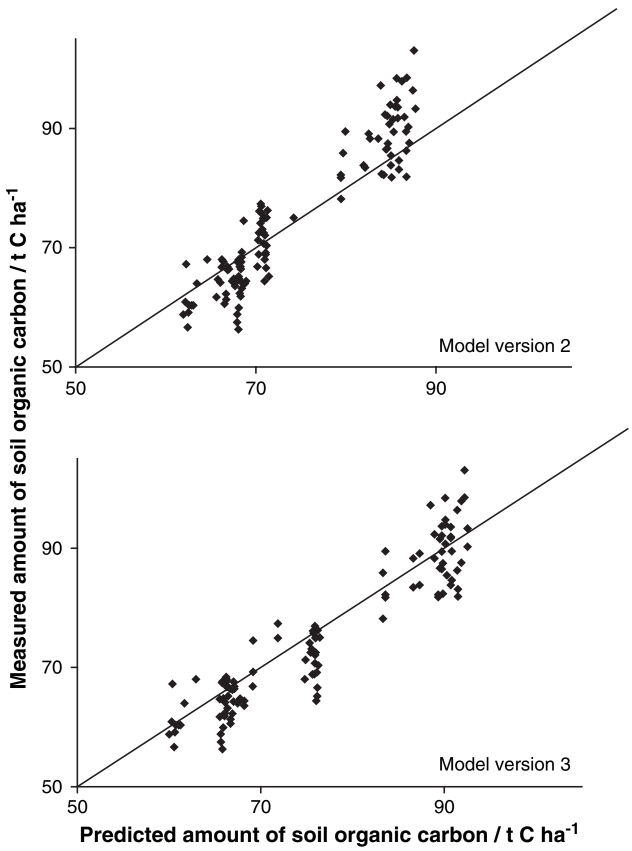

Figure 3 Measured against modelled amounts of soil organic carbon for the model versions 2 and 3. The lines indicate the 1:1 relation.

The comparison between modelled and measured results indicates that annual C inputs into the soil for the NPK treatment were much less than 3.3 t C ha^{-1} (version 1), but larger than the range of 0.67 (potatoes) to 1.21 t C ha^{-1} a^{-1} (winter wheat) (version 2, Table 3b). Optimum results were obtained for C inputs (in t C ha^{-1} a^{-1}) of 0.91 (sugar beet, first year of the crop rotation), 1.22 (spring barley, second year), 1.85 (potatoes, third year) and 2.43 (winter wheat, fourth year) (version 3, Table 3b, Figure 2). We cannot easily compare our optimum annual C inputs for the NPK treatment with the optimized annual C input of 2.6 t C ha^{-1} year^{-1} for this site reported by Coleman *et al.* (1997), because those authors considered a different depth (23 cm), they assumed a different amount of inert organic C (3 t C ha^{-1}), and they had somewhat different climatic data available. They used a mean of 1956 to 1994 for the steady-state calculation with an average temperature of 9.0°C and total sums of precipitation and evaporation of 474 and 644 mm, whereas we used the means from 1902 to 2001, which were 8.8°C, 483 mm and 598 mm. We also made different assumptions for the soil cover for the steady-state calculations (soil cover for 6 months per year compared with 9 in model versions 2 and 3) (Coleman *et al.*, 1997; K. Coleman, personal communication).

Uncertainties regarding C inputs into soils

The experimental results of Klimanek (1987, 1997) and those of others (Pätzold, 1963; Chloupek, 1972) as well as our model results for versions 2 and 3 indicate that C inputs into the soil are functions of the crop yield. However, one has to bear in mind that the production of below-ground biomass is not always correlated with the grain yields. For instance, El Sayed Fayed (1984) reported that increasing additions of mineral N fertilizer in the range of 0–120 kg N ha^{-1} gave increased wheat yields, but maximum root biomass was obtained at an addition of 40 kg N ha^{-1}. Welbank *et al.* (1974) showed for cereals that yield and root mass do not increase proportionally with application of inorganic fertilizers.

For wheat, several investigations since Klimanek (1997) and Franko (1997) have considered the production of root biomass. Kuzyakov & Domanski (2000) summarized in their review that for wheat 13% of the total C assimilated may be allocated to the roots, Kong *et al.* (2005) presented a formula with wheat roots equalling 0.22 times the above-ground biomass, and Skjemstad *et al.* (2004) used a factor of 0.4 for Australian soils. Applying these approaches for the estimation of C inputs into the soil for a wheat grain yield of 6 t dry matter ha^{-1} (or an above-ground biomass yield of 12 t ha^{-1} at a grain:straw ratio of 1) results in a range of C inputs into the soil of 1.2–2.2 t C ha^{-1} (excluding rhizodeposition). This is larger than the estimate from Franko's approach (0.9 t C ha^{-1}, excluding rhizodeposition) but in good agreement with the average root and crop residue C input of 1.6 t C ha^{-1} (2.4 t C ha^{-1} including rhizodeposition, Table 3b) summarized by Klimanek (1987, 1997).

Uncertainties regarding inert organic matter

The better performance of the model versions 2 and 3 compared with version 1 suggests that there are large amounts of inert organic matter in the soil, 82% (version 2) or 79% (version 3) of the total C of treatment 5 in 2002 (70.3 t C ha^{-1}). This finding is in a marked contrast to the result of version 1 (use of the ^{14}C measurement of the bulk soil) which suggested that only 25% of the total C is inert. However, even without modelling Figure 2 shows for all four bare fallow treatments (2, 4, 6, 8) that within 47 years only small amounts of C were lost and suggests that a passive pool (inert organic matter in the Rothamsted Carbon Model) might consist of old stabilized C (e.g. charcoal) and additional large amounts of stabilized C because of the known marked interaction of organic C with inorganic soil colloids in Haplic Chernozems.

Conclusions

The Rothamsted Carbon Model proved to be successful for the predictive modelling of the C dynamics in the Bad Lauchstädt long-term-experiment. However, a calibration using one experimental long-term treatment was required. Inputs of C by root and crop residues as summarized by Klimanek (1987, 1997) served well in the model when differentiated for sites without (minimum experimental values) and sites with fertilizer (average experimental values) when carbon from rhizodeposition was considered in addition. The model, with yield incorporated in it, may be generalized for other sites, but the inputs of C to the soil might not be a linear function of the yield as suggested by Franko (1997), but non-linear (Welbank *et al.*, 1974; El Sayed Fayed, 1984). Additionally, more experimental data on the effects of soil texture, climate, harvest technique and time of sowing on the relations between yields and root and crop residues might help to predict C input and subsequent dynamics of organic C in the soil.

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