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Review article

Effects of fertilization and soil management on crop yields and carbon stabilization in soils. A review

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Abstract – The study of sustainable land use is complex and long-term experiments are required for a better understanding of the processes of carbon stabilization. Objectives were (i) to describe for four long-term experiments the effects of fertilization and soil management on crop yields and the dynamics of soil organic carbon (SOC) and total N, and (ii) to discuss the usefulness of models for a better understanding of the underlying processes. Data of soil organic carbon and total N of four long-term experiments in Germany and China which studied the effect of fertilization (Bad Lauchstädt, Darmstadt) and tillage (Göttingen, Quzhou) were evaluated and soil organic carbon fractionation was carried out. The Rothamsted Carbon Model was used for a description and prediction of soil organic carbon dynamics as affected by fertilization and tillage in Bad Lauchstädt and Quzhou. The type of fertilizer added at common rates – either mineral N or farmyard manure – affected the crop yields only slightly, with slightly lower yields after manure application compared with mineral N fertilization. For both fertilization trials, manure applications at common rates had beneficial effects on soil organic carbon stocks in the labile pool (turnover time estimated as <10 years) and to a greater extent in the intermediate pool (turnover time estimated to be in the range of 10 to 100 years). A comparison of the effects of conventional tillage, reduced tillage and no-tillage carried out in Göttingen and Quzhou indicated only small differences in crop yields. Reduced tillage in Göttingen resulted in an increased C storage in the surface soil and C was mainly located in the mineral-associated organic matter fraction and in water-stable macro-aggregates (>0.25 mm). For Quzhou, no-tillage and conventional tillage had similar effects on total C stocks, with a greater spatial variability in soil organic carbon stocks in the no-tillage plots. Modeling required site-specific calibrations for the stock of inert organic matter for each of the sites, indicating that not all carbon stabilization processes are included in the model and that application of a model to a new site may also need site-specific adjustments before it can be used for predictions. After site-specific calibration, however, model predictions for the remaining treatments were generally accurate for the fertilization and tillage trials, which emphasizes the importance of temperature, moisture, soil cover and clay content on the decomposition dynamics of soil organic carbon and the significance of amounts and quality of carbon inputs in the soil for maintaining or increasing soil organic carbon stocks in arable soils.

soil organic matter / C dynamics / Rothamsted carbon model / tillage / fertilization / soil organic carbon (SOC)

Contents

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1. INTRODUCTION

Over the last century, agricultural production has steadily increased, mainly due to improved nutrient availability, crop breeding and crop protection. However, these improvements have often caused environmental problems, such as water pollution, trace gas emissions or soil degradation. More sustainable practices are needed to minimize the environmental impact of agricultural production and land use.

A large number of definitions for sustainable agriculture have been proposed (Cannell and Hawes, 1994; Herdt and Steiner, 1995; Kennedy and Smith, 1995; Van Loon et al., 2005) and often three elements or dimensions are incorporated: environmental (also called biological or physical), economic and social (Herdt and Steiner, 1995; Van Loon et al., 2005). Generally, however, it is agreed that agricultural systems are sustainable if they sustain themselves over a long period of time, that is, if they are economically viable, environmentally safe and socially fair (Lichtfouse et al., 2009).

Agro-ecosystems currently supply the bulk of humanity's food and fiber. Maintaining and improving soil quality is crucial if agricultural productivity and environmental quality are to be sustained for future generations (Rasmussen et al., 1998). Soil organic matter is a key element in soil quality because of its positive impact on physical, chemical and biological soil properties, such as improvement in soil structure, retention of water and plant nutrients, increase in soil biodiversity and decrease in risks of soil erosion (Reeves, 1997; Lal, 2009).

The organic matter content of a soil, which is most commonly estimated by determining the soil organic carbon (SOC) content, responds only slowly to changes in agricultural management such as crop rotation, fertilizer input, manure application or tillage. Most SOC changes require many years to be detectable by present analytical methods (Rasmussen et al., 1998). These gradual changes can only be measured with long-term experiments. Long-term agro-ecosystem experiments may therefore help to evaluate the effect of traditional and new cropping systems on soil quality and the sustainability of these systems. Long-term experiments can also serve as early warning indicators of threats to future crop production (Richter et al., 2007). In addition, long-term data sets provide reliable data for computer models. Models may be powerful tools to predict the effect of various management practices and changing climate on soil quality and SOC, provided they are based on reliable data and the appropriate model representation of the process being modeled. Together with long-term experiments, computer models may improve our understanding of the interactions between agricultural management, soil quality and the global environment (Beheydt et al., 2007; Franko, 1997; Jenkinson and Rayner, 1977; Leifeld et al., 2008; Ludwig et al., 2005, 2008; Parton et al., 2007; Powlson et al., 2008; Smith et al., 1997; Whitmore and Schröder, 2007).

The dynamics of SOC and total N have received considerable attention recently due to the link between soils and the atmospheric concentrations of greenhouse gases such as carbon dioxide and nitrous oxides. Soils can be a source or sink of greenhouse gases, with the direction and size of the net fluxes depending on land use and management (Lal, 2009). Even though climate change was not an issue when the first long-term experiments were initiated, they now provide valuable data to quantify changes in SOC and total N better to understand the underlying mechanisms better.

The objectives of the study were (i) to describe for four long-term experiments the effects of fertilization and soil management on crop yields and the dynamics of SOC and total N, and (ii) to discuss the usefulness of models – with a focus on the Rothamsted Carbon (RothC) Model – for a better understanding of the underlying processes.

2. SITE DESCRIPTIONS OF THE FOUR SELECTED LONG-TERM EXPERIMENTS

For an evaluation of the effects of fertilization on crop yields and the dynamics of soil organic carbon, long-term experiments are required, since it takes years until management effects on soil carbon pools are detectable. We chose long-term experiments which were established approximately 100 (Bad Lauchstädt) or 30 (Darmstadt) years ago. Both trials consisted of typical crop rotations with cereals and root crops and had varying fertilization treatments. The trials enabled us to study

C stabilization in silty (Bad Lauchstädt) and sandy (Darmstadt) soils.

The study of soil management effects on crop yields and C turnover processes in soil also requires long-term evaluations. Out of the large number of tillage experiments carried out (Alvarez, 2005), only a few plots are appropriate for a detailed study of C dynamics due to the data requirement of SOC models and the need for soil fractionation results. We chose three trials for our study and they were established decades (Göttingen, Germany: 1967 and 1970, Quzhou, China: 1984) ago. These plots also had crop rotations which were typical for the countries: cereals and legumes in Göttingen, and the cereals winter wheat and summer maize in Quzhou. The plots provided insights into C stabilization processes because of the experiments carried out (determination of density fractions and water-stable aggregates in Göttingen) and because of the information available which was sufficient for modeling (Quzhou).

2.1. Fertilization experiments

2.1.1. Bad Lauchstädt (Germany)

The long-term experiment in Bad Lauchstädt was established in 1902. The mean annual temperature and annual sum of precipitation are 8.8 °C and 483 mm. The soil at the site is a Haplic Chernozem (WRB, 2006) derived from loess and has a high silt content of 68% and a clay content of 21% (Blair et al., 2006). Mean bulk density in the Ap horizons is 1.35 g cm^{-3} (Ludwig et al., 2007). The crop rotation was sugar beet, spring barley, potatoes and winter wheat (Franko et al., 2007). The following treatments are considered here:

- Manure treatment: a continuous crop rotation established in 1907 with the addition of 30 t farmyard manure from cattle per hectare (approximately 2.7 t C ha^{-1}) every 2 years.
- NPK treatment: a continuous crop rotation established in 1903 with varying NPK fertilization.
- NPK and manure treatment: a continuous crop rotation established in 1907 with varying NPK fertilization and the addition of 2.7 t C ha^{-1} in the form of manure from cattle every 2 years.
- Control treatment: a continuous crop rotation established in 1903 without any fertilization.

The N fertilization in the NPK and NPK and manure treatments depended on the crop and was varied according to the standard agricultural practices of the time, 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 has varied according to the contents of inorganic N in the soils (Körschens et al., 1994a).

The yields were subjected to a nonparametric statistical test (Mann-Whitney U-test) to check significant differences ($P \leqslant 0.05$) between the treatments.

2.1.2. Darmstadt (Germany)

The experimental trial is located near Darmstadt, Germany, and was established in 1980. The mean annual temperature is 9.5 °C and the annual sum of precipitation is 590 mm. The soil is a Haplic Cambisol (WRB, 2006) which developed on alluvial fine sands of the former river Neckar (Bachinger, 1996). The soil has a sand and clay content in the surface soil of 86% and 5%, respectively, and bulk density ranges from 1.35 to 1.41 g cm^{-3} (Heitkamp et al., 2009). Before the trial started, the site was managed as part of a biodynamic farm for at least 20 years (Abele, 1987). In 1980, nine treatments (four replicates each) were arranged in a strip design, with the factors being type of fertilizer and its application rate. Apart from fertilization, all management practices were the same. The crop rotation consisted of legumes (mainly red clover or lucerne), spring wheat, root crops (mainly potatoes) and winter rye (Raupp and Oltmanns, 2006). Residues of potatoes were incorporated into the soil. Aboveground legume biomass was removed from the plots. Oil radish or white mustard were sown as winter catch crops, usually after spring wheat. From 1981 to 1984 fertilizer application rates were chosen with the aim of obtaining equal yields for the respective manure and mineral fertilizer treatments discussed below. The following treatments considered here have been in place since 1985:

- NPK_H and straw treatment: high application rate of mineral fertilizer (150 kg N ha^{-1} to root crops or 100 kg N ha^{-1} plus 40 kg N ha^{-1} as second application to cereals) plus straw incorporation.
- NPK_L and straw treatment: low application rate of mineral fertilizer (50 kg N ha^{-1} to root crops or 60 kg N ha^{-1} to cereals) plus straw incorporation.
- $Manure_H$ treatment: high application rate of rotted manure: 150 kg N ha^{-1} to root crops or 100 kg N ha^{-1} plus 40 kg N ha^{-1} with urine (second application) to cereals.
- $Manure_L$ treatment: low application rate of rotted manure: 50 kg N ha^{-1} to root crops or 60 kg N ha^{-1} to cereals.

In the four-year course of the crop rotation from 2003 to 2006, measured mean annual C inputs (t ha^{-1} $year^{-1}$) with straw were between 1.0 and 1.2 in the NPK and straw treatments, whereas measured differences in C inputs from manure were more pronounced and ranged from 0.6 to 1.3 in the manure treatments (Heitkamp et al., 2009).

To account for the structure of the strip design we applied a mixed model in order to test for significant ($P \leqslant 0.05$) effects of the treatments on crop yields and SOC fractions (Heitkamp et al., 2009). The field trial was divided into main rows and main columns. Thus, the following statistical model with the notation proposed by Piepho et al. (2003) was used:

$$R_k + C_l + RC_{kl} + T_i + A_j + TA_{ij}{:}TR_{ik} + ARC_{jkl} + TARC_{ijkl} \quad (1)$$

where R_k is the effect of the *k*-th main row, C_l is the effect of the l-th main column, RC_{kl} is the effect of the kl-th main row and main column interaction, T_i is the effect of the i-th fertilizer type, A_j is the effect of the j-th fertilizer rate, TA_{ij} is the effect of the ij-th fertilizer type and rate interaction, TR_{jk}

is the error of the jk-th fertilizer type and main row interaction, ARC_{jkl} is the error of the jkl-th fertilizer rate and main row and main column interaction, and $TARC_{ijkl}$ is the error of the ijkl-th subplot. Effects listed before the colon are fixed whereas those after the colon are random; the residual terms are underlined. Differences between means were tested using least significant differences (LSD) at $P \leqslant 0.05$.

2.2. Tillage experiments

2.2.1. Göttingen (Germany)

Two experimental trials near Göttingen, Germany, were established in 1970 (Garte Süd) and 1967 (Hohes Feld). The mean annual sum of precipitation is 645 mm and mean annual temperature is 8.7 °C. The soil type of both sites is a Haplic Luvisol (WRB, 2006) derived from loess (Ehlers et al., 2000; Reiter et al., 2002). The soil texture (0–30 cm) in Garte Süd consists of 15.1% clay, 72.7% silt and 12.2% sand (Ehlers et al., 2000) and in Hohes Feld of 17.2% clay, 66.5% silt and 16.4% sand. Bulk densities (in g cm^{-3}) in the 0–5 cm depths are 1.36 (conventional tillage) and 1.25 (reduced tillage) in Garte Süd, and 1.32 (conventional tillage) and 1.40 (reduced tillage) in Hohes Feld (Jacobs et al., 2009). The same crops were grown at both sites. From 2002 to 2007, the following crops were grown: forage maize, winter wheat/mustard, pea, winter wheat and winter wheat. All residues were incorporated by the respective tillage operations. The following treatments are considered here:

- Garte Süd, conventional tillage: conventional tillage with a regular moldboard plow to 25 cm depth and seedbed preparation with a rotary harrow or rototiller in Garte Süd.
- Garte Süd, reduced tillage: reduced tillage to 5–8 cm depth with a rotary harrow or rototiller for stubble cultivation and seedbed preparation in Garte Süd.
- Hohes Feld, conventional tillage: conventional tillage to 25 cm depth as described above in Hohes Feld.
- Hohes Feld, reduced tillage: reduced tillage to 5–8 cm depth as described above in Hohes Feld.

The experimental sites have been fertilized with 161 kg N ha^{-1} $year^{-1}$ over the past 10 years with the exception of the cultivated legumes. Additionally, 60 kg K ha^{-1} and 9 kg Mg ha^{-1} fertilizers were applied to both sites in 2004 and 2005, with 169 kg K ha^{-1} and 25 kg Mg ha^{-1} added in 2006. The Hohes Feld site was fertilized with 46 kg P ha^{-1} in 2004 and 2005, whereas the Garte site has not received any P fertilizer since 1997.

2.2.2. Quzhou (China)

The experimental trial was conducted in Quzhou County, in the middle of the North China Plain and was established in 1984. The county has a continental monsoonal climate, and the mean annual air temperature is 13.3 °C and the annual sum of precipitation is 482 mm, with 60% of the precipitation occurring from July to September. The soil is an Aquic Cambisol (WRB, 2006) 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 and bulk density is 1.35 g cm^{-3} (Ludwig et al., 2010). Before the field trial the site was wasteland because of serious saline-alkalinization due to non-sustainable agriculture. The crop rotation consisted of winter wheat and summer maize in each year. The following treatments are considered here:

- Conventional tillage and control: conventional tillage down to 20 cm depth and no fertilization.
- Conventional tillage and $N_2P_2straw_2$: conventional tillage down to 20 cm depth and application of 187 kg urea-N ha^{-1} $year^{-1}$, 150 kg P_2O_5 ha^{-1} $year^{-1}$ and 4.5 t dry matter (DM) straw ha^{-1} $year^{-1}$ which equaled 2.03 t C ha^{-1} $year^{-1}$.
- No-tillage and $N_0P_2straw_1$: no-tillage and application of 150 kg P_2O_5 ha^{-1} $year^{-1}$ and 2.25 t DM straw ha^{-1} $year^{-1}$ which equaled 1.01 t C ha^{-1} $year^{-1}$.
- No-tillage and $N_2P_1straw_0$: no-tillage and application of 187 kg urea-N ha^{-1} $year^{-1}$ and 75 kg P_2O_5 ha^{-1} $year^{-1}$.

In early June each year after harvest, straw was removed from the fields and straw from winter wheat was applied at the rate described above in the treatments with moderate and large straw additions. Plots of all treatments were irrigated with 570 mm water per year (mainly groundwater) 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.

The yields were subjected to a nonparametric statistical test (Mann-Whitney U-test) to check significant differences ($P \leqslant 0.05$) between the treatments.

3. MODELING METHODOLOGY

A number of SOC models have been developed in order to gain further insights into the C dynamics in soils. Gabrielle et al. (2002) tested the usefulness of the soil-plant models CERES, NCSOIL, SUNDIAL and STICS and the RothC model for a description of the C dynamics in soil and reported that the RothC model was more useful than the others. Moreover, the RothC model has been widely used in soil science and has been independently tested in soils of Europe, Africa, America and Australia (e.g., Ludwig et al., 2003, 2005, 2007; Shirato and Yokazawa, 2006; Skjemstad et al., 2004; Smith et al., 1997).

We used the RothC model version ROTHC26-3 (Coleman and Jenkinson, 1999; Jenkinson and Rayner, 1977; Smith et al., 1997) which includes the following pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (Cmic), humified organic matter (HUM) and inert organic matter (IOM) to calculate the C dynamics in the long-term treatments. 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),

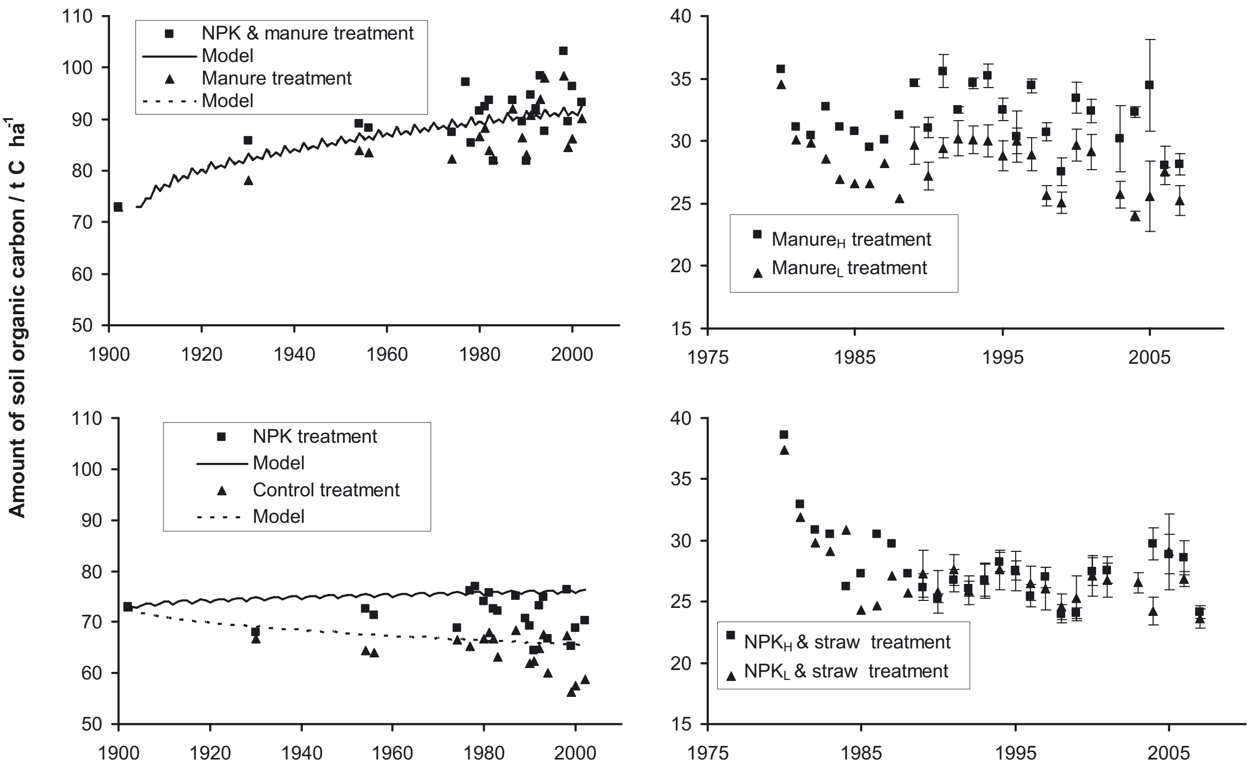

Figure 1. SOC stocks during the experimental period for the long-term experiments in Bad Lauchstädt (left, Ap horizon, 0–30 cm), and Darmstadt (right, Ap horizon, 0–25 cm). Measured (symbols) and modeled (lines) data (modified after Ludwig et al., 2007 and Heitkamp et al., 2009).

0.3 (RPM), 0.66 (Cmic) and 0.02 (HUM) as suggested by Coleman and Jenkinson (1999). Data requirements of the model are monthly mean air temperature, monthly precipitation, monthly open pan evaporation, the soil depth studied and the clay content of the soil, the DPM/RPM ratio for the crops (default value is 1.44), and the months in which the soil is covered by vegetation. For the climate data, averages of the years 1902 until 2001 (Bad Lauchstädt) or of the years 1983 until 2003 (Quzhou) were taken (Ludwig et al., 2007, 2010). The parameterization for the remaining required input data – the monthly input of plant residues and the amount of IOM – is described below.

We applied this model to the trials in Bad Lauchstädt and in Quzhou. The Darmstadt trial had to be excluded from the modeling, since the large initial decreases in SOC stocks (Fig. 1) could not be explained plausibly and may have been due to the fact that the initial sampling design (one sample for the entire field in 1980) was not adequate and did not catch the soil heterogeneity at the site. For Göttingen, information on initial SOC stocks was not available.

For Bad Lauchstädt, a site-specific calibration was required. We initialized and calibrated the model to the site by using one experimental treatment (described below). The remaining treatments were used for a subsequent independent retrospective prediction (described below) to assess the usefulness of the model approach. We assumed that a steady state existed in 1902 and the parameterization was as follows (Ludwig et al., 2007):

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 the fertilization treatments, the average experimental values for the crop and root residues from Klimanek (1987, 1997) were used as C inputs. For the no-fertilization treatment, where the yields were exceptionally small (Tab. I), the minimum experimental values of crop and root residues in surface soils (0–30 cm) summarized by Klimanek (1987, 1997) were used in the model. Additionally, we considered the C input by rhizodeposition to be 50% (winter wheat and spring barley) and 35% (sugar beet and potato) of the C input by crop and root residues (Ludwig et al., 2007).

2. Initialization and calibration: the amount of IOM and the annual C inputs until 1902 were estimated from the initial and final C stocks of one long-term treatment (NPK fertilization from 1903 until 1955 followed by a bare fallow until 2003, Ludwig et al., 2007) and the C inputs from 1903 until 1955, as described above. The values obtained to match these C stocks were 1.3 t C ha^{-1} $year^{-1}$ for the annual C inputs until 1902 and IOM = 55.3 t C ha^{-1}.

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

Table I. Yields of grain (spring barley, winter wheat, spring wheat, summer maize, peas), of the main product (sugar beet, potato) and aboveground biomass (silage maize, berseem clover) for different crops (means and standard errors). Yields in dry matter (DM) are given including 14% water content. Different characters indicate significant differences between the yields for each crop ($P \leqslant 0.05$). DM: dry matter; FM: fresh matter.

Site and crop	Treatment			
Bad Lauchstädt[1]	NPK and manure	Manure	NPK	Control
Sugar beet (t FM ha^{-1})	54.5 (4.2)[c]	48.7 (3.7)[b]	52.6 (4.6)[c]	22.2 (2.5)[a]
Spring barley (t DM ha^{-1})	5.26 (0.54)[b]	4.49 (0.37)[b]	4.61 (0.34)[b]	2.39 (0.22)[a]
Potato (t FM ha^{-1})	37.6 (2.5)[b]	31.5 (2.8)[b]	32.5 (3.0)[b]	9.91 (1.1)[a]
Winter wheat (t DM ha^{-1})	6.53 (0.55)[b]	5.98 (0.49)[b]	6.71 (0.52)[b]	3.52 (0.26)[a]
Darmstadt[2]	$Manure_H$	$Manure_L$	NPK_H and straw	NPK_L and straw
Spring wheat (t DM ha^{-1})	3.4 (0.2)[a]	2.8 (0.2)[a]	4.1 (0.2)[b]	3.8 (0.1)[b]
Potato (t FM ha^{-1})	21.3 (1.0)[b]	17.8 (0.3)[a]	26.1 (0.9)[c]	19.1 (0.9)[ab]
Winter rye (t DM ha^{-1})	4.1 (0.2)	3.3 (0.4)	3.9 (0.2)	3.8 (0.3)
Berseem clover (t DM ha^{-1})	5.1 (0.2)[c]	3.3 (0.2)[b]	3.1 (0.3)[ab]	2.8 (0.3)[a]
Göttingen[3]	Garte Süd, conventional tillage	Garte Süd, reduced tillage	Hohes Feld, conventional tillage	Hohes Feld, reduced tillage
Winter wheat (t DM ha^{-1})	7.1 (0.6)	6.9 (0.7)	7.4 (0.4)	7.3 (0.6)
Silage maize (t DM ha^{-1})	19.2	18.3	20.7	19.9
Peas (t DM ha^{-1})	2.5	2.3	3.3	2.0
Quzhou[4]	Conventional tillage and control	Conventional tillage and $N_2P_2straw_2$	No-tillage and $N_0P_2straw_1$	No-tillage and $N_2P_1straw_0$
Winter wheat (t DM ha^{-1})	1.23 (0.19)[a]	5.06 (0.39)[c]	1.27 (0.21)[a]	3.40 (0.49)[b]
Summer maize (t DM ha^{-1})	2.67 (0.39)[a]	7.90 (0.44)[b]	2.72 (0.28)[a]	7.19 (0.66)[b]

[1] Means from 1961 to 2002 (from Ludwig et al., 2007).
[2] Means (n = 4) for the crops cultivated in the period from 2003 to 2006 (from Heitkamp et al., 2009).
[3] Yields for the period from 2002 to 2006.
[4] Means from the Quzhou trial (Ludwig et al., 2010).

For Quzhou, a site-specific calibration was also required and we assumed that a steady state existed by the end of 1984. The parameterization was as follows (Ludwig et al., 2010):

1. C input: C input was calculated from the aboveground yields of grain (Tab. I) 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):

$$C_{input} = (K_{RHR} + F_{RHR} \times yield) \times 1.5, \tag{2}$$

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

2. Initialization and calibration: the stock of IOM and C inputs until 1984 (assumption of steady state conditions) were optimized iteratively in order to match the measured C stock in 1984 and by using equation (2) from the beginning of 1985 onwards to also match the measured C stock in the conventional tillage and control treatment in 2002. This resulted in an IOM stock of 10.2 t C ha^{-1} and annual C inputs until 1984 of 0.86 t C ha^{-1} $year^{-1}$.

3. Prediction: predictions for the other three treatments (Fig. 2) were carried out by using equation (2) and the measured straw inputs.

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):

$$RMSE = \frac{100}{\overline{O}} \sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n}, \tag{3}$$

$$EF = \frac{\sum_{i=1}^{n} (O_i - \overline{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \overline{O})^2}, \tag{4}$$

$$E = \frac{100}{n} \sum_{i=1}^{n} (O_i - P_i)/O_i, \tag{5}$$

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

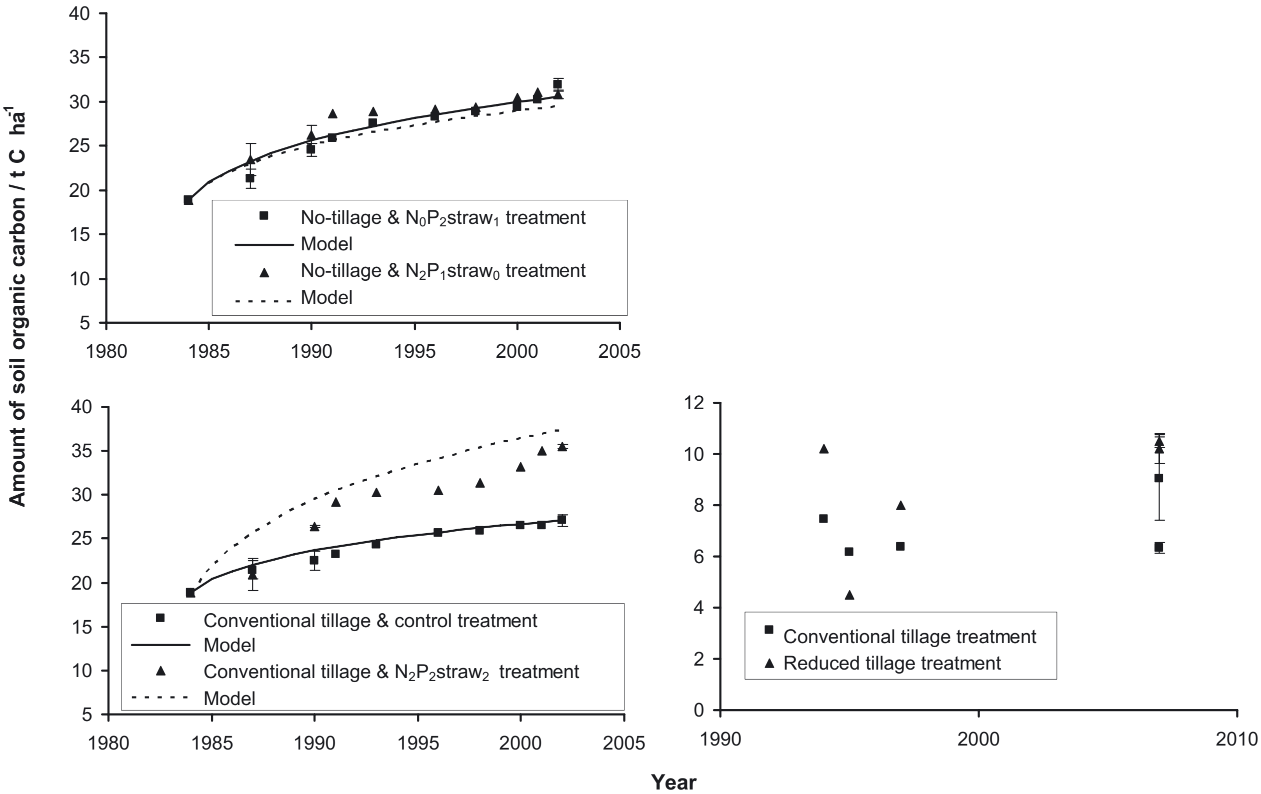

Figure 2. SOC stocks during the experimental period for the long-term experiment in Quzhou (left, conventional tillage: Ap horizon, 0–20 cm; no-tillage: Ah horizon, 0–20 cm) and Göttingen (right, Garte Süd, conventional tillage: part of the Ap horizon, 0–5 cm; reduced tillage: Ap horizon, 0–5 cm). Measured (symbols) and modeled (lines) data (modified after Ludwig et al., 2010 and Jacobs et al., 2009).

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.

4. RESULTS AND DISCUSSION

4.1. Sustainable land use: effects of fertilization

4.1.1. Yields

In the Bad Lauchstädt trial, for all treatments and crops, yields of the main products (sugar beet, potato) or grain (barley, wheat) were less between 1903 and 1960 (not shown) than they were from 1961 to 2002 (Tab. I). The yield increase from 1961 onwards is probably mainly because of increased N additions in the NPK treatments, the use of varieties with larger yield potentials and optimized use of growth promoters and pesticides (Körschens et al., 1994a). From 1961 to 2002, the combined application of NPK fertilizer and manure gave the largest yields for sugar beet (significantly different from the other treatments), spring barley and potato, whereas for winter wheat the NPK treatment had the largest yields (Tab. I). For all four crops, yields in the manure treatments were slightly lower than in the NPK treatments. However, temporal variability in all treatments was large (Tab. I). The control treatment had exceptionally small yields, significantly different from the other treatments.

In Darmstadt, the yields were much less compared with those in Bad Lauchstädt (Tab. I). Overall, crops yielded between 40 and 70% of the German average (in t ha^{-1} in the years of cultivation, spring wheat: 5.3, potatoes: 44.2, rye: 5.1, clover/grass-clover: 8.4, Statistisches Bundesamt Deutschland, 2009), due to the relatively dry site conditions and the low soil fertility of the sandy Cambisol. Only a few long-term experiments in Europe exist on low-fertility sandy soils. In the fertilization experiment in Thyrow, Germany (15 t manure ha^{-1} year^{-1}), potato yields were comparable (20 t ha^{-1}, Ellmer and Baumecker, 2005) with those of Darmstadt, where they reached 17.8 and 21.3 t ha^{-1} in the plots fertilized with low and high rates of manure, respectively. In contrast, the winter rye yield in Darmstadt (Tab. I) was remarkably higher than the yield at the Sandmarken site in Askov, Denmark (1.7 t ha^{-1}) (Edmeades, 2003).

In Darmstadt, the largest yields were observed for the treatments with an input of 140 (spring wheat) to 150 (potatoes) kg N ha^{-1} year^{-1} (manure$_H$ and NPK$_H$ and straw treatments), where the NPK$_H$ and straw application resulted in 0.7 t DM ha^{-1} more grain of spring wheat and 4.8 t FM ha^{-1}

more potatoes than the $manure_H$ treatment. Overall, these data suggest that yields in Darmstadt are limited by N availability. This is in line with Raupp and Oltmanns (2006), who showed by analyzing all years that N availability has a strong effect on yield at this site, especially for potatoes and rye in high-yielding years, while the other two crops also depended on water availability.

In summary, low ($manure_L$ and NPK_L and straw treatments) and no fertilization (control treatment in Bad Lauchstädt) gave generally low yields and manure application at common rates gave similar, but slightly lower yields than mineral N fertilizer at common rates for both sites studied.

4.1.2. SOC and total N stocks

In Bad Lauchstädt, 96 years of different fertilization regimes resulted in pronounced differences in the stocks and properties of soil organic matter (Blair et al., 2006; Ludwig et al., 2007; Smith et al., 1997, Fig. 1). For instance, mean values (1998–2002, standard errors are given in parentheses) of SOC stocks in t C ha^{-1} decreased in the order 95.6 (2.9) for the NPK and manure treatment >89.9 (3.1) for the manure treatment >70.2 (2.3) for the NPK treatment $\gg$ 60.0 (2.5) for the control treatment, which emphasizes the importance of manure for the buildup of SOC stocks and contents. However, the increased SOC and total N concentrations, reached after 96 years of manure applications, were still about one-third lower than in the reference grassland soil, which was most likely due to the opposing effect of tillage, which increases the mineralization rate of soil organic matter (Blair et al., 2006). Larger manure applications would be needed to offset the effects of tillage, as can be seen from the results of another experiment carried out at the same site. In this "extreme manure experiment" with an application of 200 t manure ha^{-1} $year^{-1}$ for 20 years, soil C increased to the concentrations found in the reference grassland soil. However, with such high manure applications, losses of N, particularly through leaching of nitrate to the groundwater, are very high, making such a treatment unsustainable (Blair et al., 2006; Körschens et al., 1994b).

In Darmstadt, twenty-seven years of different fertilization regimes resulted in significantly higher stocks of SOC and total N in the soils with manure additions compared with those with additions of straw and mineral fertilizer (Fig. 1), and increasing applications of manure increased the stocks slightly but not significantly (Fig. 1, Heitkamp et al., 2009). Overall, these findings are in accordance with those of other authors for several soil types with loamy and sandy textures (Christensen, 1996; Weigel et al., 1998). However, the initial SOC stocks determined in the early eighties should be interpreted cautiously, since replicate measurements were absent and the large initial losses of SOC in the NPK and straw treatments are difficult to explain, considering that changes in SOC stocks generally take place at a much lower rate (see e.g., the modeled temporal dynamics of SOC stocks in Bad Lauchstädt and Quzhou discussed below). In Darmstadt, SOC stocks had already achieved steady state conditions (an approximate balance of C inputs and outputs) in all treatments approximately 10 years after the beginning of the trial (Fig. 1, Raupp, 2001), suggesting that at sandy sites steady state conditions after changed fertilization management may be reached faster compared with loamy soils.

4.1.3. C and N storage in different soil fractions

In order to understand the fate of the organic matter inputs by manure, roots and straw better, Blair et al. (2006) carried out an oxidation with $KMnO_4$ for the Bad Lauchstädt soils with and without manure additions. Overall, labile SOC increased by 2.1 g kg^{-1} in the treatments with manure additions, compared with those without manure additions (Blair et al., 2006). We calculated the effects of manure additions on the content of intermediate C by subtracting the amounts of labile SOC (Blair et al., 2006) and passive SOC (obtained in the modeling procedure as described in Sect. 3) from the total SOC content. The calculation suggested that the effect of manure was most pronounced on the intermediate C pool (Tab. II). However, the interpretation should be taken with care, since the usefulness of $KMnO_4$ for the determination of labile C has been debated and since the value for the passive pool is large, as discussed by Ludwig et al. (2007). Moreover, the inaccuracy of the difference calculation (for the plots without manure additions, the sum of the labile and passive pool is 16.7 g kg^{-1} compared with the SOC content of 16.2 g kg^{-1}) indicates that the results are useful only as an approximation.

In Darmstadt, stocks of the modeled labile C and N pools (turnover times up to 462 days for C and up to 153 days for N) were not influenced by the type of fertilizer (Tab. II) but depended significantly on the application rate and ranged from 7 to 13% of SOC and from 4 to 5% of total N (Heitkamp et al., 2009). In contrast, the size of the calculated intermediate C pool was greater for the manure treatments (Tab. II), and depended significantly on the interaction between fertilizer type and rate. The intermediate N pool was not affected by fertilizer type or rate. Passive C and N pools, as experimentally revealed by oxidation with disodium peroxodisulfate ($Na_2S_2O_8$), were independent of the treatments (Heitkamp et al., 2009). Overall, labile and intermediate pools were affected differently by the fertilizer type and the application rate. For Darmstadt, turnover times of the labile C pool (given above) and passive C pool (turnover time $\gg$ 600 years) were quantified. A quantification of the turnover time was not carried out for the intermediate pool of the Darmstadt soil nor for any of the three pools in the Bad Lauchstädt soil, and we use the estimation by von Lützow et al. (2008), who estimated that the labile C pool has a turnover time of less than 10 years, the intermediate pool has a turnover time of 10 to 100 years and the passive pool has a turnover time greater than 100 years.

In summary, manure applications at common rates had beneficial effects on SOC stocks in the labile pool (turnover time estimated as <10 years) and to a greater extent in the intermediate pool (turnover time estimated to be in the range of 10 to 100 years) at both sites studied. However, one has to keep in mind that because the ratio of nutrients in manures is different from the ratio of nutrients removed by common

Table II. Total SOC contents in the surface soils (Bad Lauchstädt: 0–10 cm, Darmstadt: 0–25 cm) and contents of labile C, intermediate C and passive C.

Site and plots	SOC	Labile C pool	Intermediate C pool ($g\ kg^{-1}$)	Passive C pool
Bad Lauchstädt[1]				
Plots with manure additions	22.0	5.1	3.3	13.7
Plots without manure additions	16.2	3.0	0.0	13.7
Darmstadt[2]				
$Manure_H$	8.1	1.1	4.9	2.2
$Manure_L$	7.5	0.6	4.5	2.4
NPK_H and straw	7.2	1.0	3.9	2.2
NPK_L and straw	6.7	0.6	4.0	2.0

[1] Organic Contents (SOC) and labile C pool (determined by $KMnO_4$ oxidation) were taken from Blair et al. (2006), the passive pool (inert organic matter) from a model calibration (Ludwig et al., 2007) and the intermediate pool was calculated as difference (the negative value for the intermediate pool for the plots without manure additions was set to zero).
[2] Data were recalculated from Heitkamp et al. (2009), the labile pools (turnover times up to 462 days) were determined by an incubation, the passive pool (turnover $\gg$ 600 years) by a chemical fractionation and the intermediate pool was calculated as difference.

crops, excessive accumulation of some nutrients, especially P and N, may arise from the long-term use of manures, relative to the use of mineral fertilizers (Edmeades, 2003). In the Darmstadt and Bad Lauchstädt trials, however, none of these effects have been observed. Moreover, Edmeades (2003) suggested that the long-term use of manure may result in greater runoff of P, leaching of N, greater P leaching losses from sandy soils and overall poor water quality because there may be an increased demand for chemical oxygen.

4.1.4. Model results on the effects of fertilization on the SOC dynamics

The predictions of the RothC model agreed well with the measured SOC stocks in the different long-term treatments of the Bad Lauchstädt trial (Fig. 1). The model efficiency was 0.86 and the root mean square error was small (6.07). However, the relative error E of –2.31 indicated a slight bias in the total difference between predictions and measurements. An assumed uncertainty of the C inputs of 25% covered most of the experimental data (Ludwig et al., 2007). Overall, the test of the model indicated (i) the need for site-specific calibration using data from one experimental treatment as described above, and (ii) the need for either experimental data from actual measurements of crop and root residues or the use of published functions that relate C inputs to crop yields. The good agreement between measured and modeled SOC stocks in the treatments (Fig. 1) also indicates that the factors considered in the RothC model such as temperature, moisture, soil cover and clay content are key factors for the decomposition dynamics of SOC. Moreover, the input of organic matter can be expressed as a ratio of decomposable (DPM) to resistant plant material (RPM) of 1.44 (thus, DPM being 59% and RPM being 41%) for most agricultural crops and for the more stabilized manure as 49% DPM, 49% RPM and 2% HUM. However, the need for site-specific calibration indicates several shortcomings of the RothC model. A comparison between a conceptual model derived from experiments using ^{13}C and ^{14}C data and the RothC model indicated that the RothC model has considerably less counterparts for the intermediate (HUM pool) and passive pools (IOM pool) than the conceptual model. Site-specific calibration may be required for those sites where dynamics of black C and the interactions of SOC with mineral surfaces have a significant impact on soil organic matter dynamics (Ludwig et al., 2008).

4.2. Sustainable land use: effects of soil management

4.2.1. Yields

In both long-term trials, Göttingen and Quzho, different tillage systems did not affect crop yields markedly (Tab. I). In Göttingen, grain yields of winter wheat showed temporal variability and were almost identical between the two tillage systems – conventional and reduced tillage. However, yields of silage maize and peas were slightly higher for the conventional tillage system (Tab. I).

In Quzhou, tillage systems were much less important for the yields than the fertilization management. Grain yields for winter wheat and summer maize depended significantly on N availability (Tab. I) and to a smaller extent on P availability, as indicated by the yields for additional treatments such as no-tillage and $N_2P_1straw_0$ (grain yields: 3.4 (winter wheat) and 7.2 t DM ha^{-1} (summer maize)) and conventional tillage and $N_1P_2straw_0$ (grain yields: 4.8 (winter wheat) and 7.1 t DM ha^{-1} (summer maize), Ludwig et al., 2010). Overall, conventional tillage and no-tillage gave similar yields, provided that N and P were sufficiently available. The yields for winter wheat and summer maize are in a similar range to those reported for a fertilization trial in Changping, northern China (Guo et al., 2007).

Similarly to our results, Alvarez and Steinbach (2009) reported for the Argentine Pampas that wheat and maize yields were similar between no-tillage, reduced tillage and conventional tillage, provided that N fertilization was carried out. Without fertilization, yields under no-tillage and reduced tillage were less when compared with conventional tillage. Triplett and Dick (2008) emphasized that no-tillage is a very effective erosion control measure and improves water- and fertilizer-use efficiency so that many crops yield better under no-tillage than under tilled systems. However, in organic farming systems, where synthetic herbicides are not used, yields under reduced tillage or no-tillage might decline markedly compared with conventional tillage due to increased competition with weeds. Berner et al. (2008) reported for a Swiss tillage trial that wheat and spelt yields decreased by 14% and 8%, respectively, with reduced tillage compared with conventional tillage, but sunflower yield was slightly higher with reduced tillage.

4.2.2. SOC and total N stocks

Soil tillage has long been identified as a factor that weakens soil structure, which in turn results in soils being more prone to erosion and compaction. It also aerates the soil, which leads to a loss in soil organic matter. For the Garte site, Stockfisch et al. (1999) found that after 20 years of reduced tillage, SOC, total N and Cmic were concentrated in the top 5 cm of the soil profile. In the 50-cm soil profile, the SOC and total N stocks of the soil under conventional tillage were 65 t ha^{-1} and 6.8 t ha^{-1}, respectively, which was about 5 t ha^{-1} less SOC and 1 t ha^{-1} less total N, compared with the soil under reduced tillage, but differences were not significant. For the same trial, after 37 years of different management, differences in SOC contents were similar: in the soil under reduced tillage, the SOC contents were 16.9 and 12.0 g kg^{-1} in the surface soil (0–5 cm) and subsoil (10–20 cm), respectively. These SOC contents corresponded to an increase of 12% and 19% in the surface soil and subsoil, respectively, compared with the soil under conventional tillage (Jacobs et al., 2009), but spatial and temporal variability was marked (Fig. 2, Jacobs et al., 2009). Compared with SOC, total N was more affected by tillage treatment in the surface soil, but less in the subsoil. The decrease in total N with depth was also less pronounced than with SOC, resulting in a narrower C to N ratio in the subsoil.

The stock of SOC built up during several years of reduced tillage, however, may be lost even due to one plowing event, indicating the labile nature of the built-up SOC. For example, Stockfisch et al. (1999) found that plowing the 20-year-old soil under reduced tillage destroyed the stratification of soil organic matter. Moreover, during the winter months from November to March, the SOC and total N, accumulated under reduced tillage, were completely lost. Likewise, Koch and Stockfisch (2006) reported that after 7 to 9 years of reduced tillage, one plowing operation resulted in a substantial loss of organic matter.

In Quzhou, SOC stocks increased in all conventional tillage and no-tillage treatments in the experimental period (Fig. 2), even in the no-fertilization treatment (conventional tillage and control), indicating that the period of non-sustainable management and wasteland before the trial severely reduced SOC stocks. We calculated the C inputs into the soil using the approach by Franko (1997) which relates C inputs to crop yield by additionally considering rhizodeposition (Eq. (2)) and considering the measured straw inputs. The calculated C inputs showed (with one exception) the same order of increasing annual C inputs for the conventional tillage treatments as the order of SOC stocks for the different treatments (Ludwig et al., 2010). Overall, during the 18 years of the trial, the only marked difference between conventional tillage and no-tillage was a greater spatial variability in SOC stocks in the no-tillage plots. In his review, Alvarez (2005) reported for paired data from 161 sites with contrasting tillage systems that under conservation tillage (reduced tillage and no-tillage), SOC content was on average 2.1 t ha^{-1} greater than under conventional tillage. 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} (Alvarez, 2005).

4.2.3. C and N storage in different soil fractions

Density fractionation of the surface soils (0–5 cm) from the Garte Süd and Hohes Feld sites indicated that it was mainly the mineral-associated organic matter which contributed to the increased storage of C and N under reduced tillage rather than the particulate organic matter fraction (Jacobs et al., 2009). Thus, the results suggested that the mineral-associated fraction is quite susceptible to degradation when the field is plowed.

Reduced tillage increased the abundance of water-stable aggregates (Jacobs et al., 2009). For Garte Süd and Hohes Feld, water-stable macro-aggregates (>0.25 mm) were on average 2.6 times more abundant under reduced tillage than under conventional tillage. It was mainly the surface soil which contributed to this difference, as in the subsoil there was no significant difference in the abundance of water-stable macro-aggregates. The increased stability may be explained by the increased SOC concentrations in all aggregate classes. The increased aggregate stability translates into an improved stability of the bulk soil. For instance, on plots that had been under conventional tillage and reduced tillage for 24 years, Ehlers et al. (2000) studied the effect of heavy loads on soil properties. While one plot was left unloaded, the others were compacted with graded loads of 2 × 2.5 t (light), 2 × 5 t (medium) and 6 × 5 t (heavy; wheeling frequency × wheel load). Barley was planted in the following spring. The light load caused a significant yield decrease of 50% in soil under conventional tillage, while in the soil under reduced tillage, it needed the heavy load to induce a yield decrease of a similar magnitude.

4.2.4. Model results on the effects of soil management on the SOC dynamics

Only limited information is available on the quantitative effects of tillage on SOC dynamics by using models (Liu et al., 2009; Ludwig et al., 2010). A reason for the small number of studies is probably that most SOC models assume spatial homogeneity, which is matched to a greater extent by conventional tillage than by reduced tillage or no-tillage.

Modeling for the Quzhou site indicated successful predictions of SOC dynamics for the different fertilization and tillage treatments (Fig. 2). However, as also reported for the fertilization trial in Bad Lauchstädt, a site-specific calibration was required using one experimental treatment (conventional tillage and control). The good prediction accuracy of the C dynamics in the no-tillage experiments may, however, not be generalizable to other tillage trials, since no-tillage did not have a specific effect on SOC stocks for the Quzhou trial.

5. CONCLUSIONS

Overall, the results of the four long-term trials on silty and sandy soils indicated that application of either mineral fertilizer or manure with common agricultural practices resulted in only slightly different crop yields. A comparison of the long-term effects of conventional tillage, reduced tillage and no-tillage on crop yields also showed only slight differences between the treatments. Stocks of SOC, however, were beneficially affected by manure applications, and the increase in SOC was evident in the labile (turnover time <10 years) and intermediate (estimated as 10 years < turnover time <100 years) pools. Soil management had only small effects on SOC stocks.

The SOC dynamics were successfully predicted for the fertilization and tillage experiments using the RothC model, indicating that the main factors which govern C inputs (as estimated from yield-dependent functions) and C mineralization are quantitatively understood. However, prior to the predictions site-specific calibrations were necessary, which shows that the RothC model may be further improved to include more carbon stabilization processes.

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