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Modelling soil organic matter dynamics on a bare fallow Chernozem soil in Central Germany

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ABSTRACT

Soil organic matter (SOM) can be characterised by soil organic carbon (SOC) and/or total nitrogen (TN). The observed dynamics of SOC and TN in the topsoil of a 28-year-old fallow experiment on Haplic Chernozem was modelled using the Candy Carbon Balance (CCB) model. This study selected two treatments from this experiment where the soil was kept bare with mechanical or chemical (herbicides) treatments. The CCB model was improved to include the SOC related change of soil physical parameters and dynamic handling of the physically stabilised SOM pool. Over 28 years of bare fallow the top soil lost about 10 t/ha of SOC and > 1 t/ha of TN. The results from observation and modelling reflected the increased SOM turnover due to soil tillage. The modelled size of the physically stabilised SOC pool was about 55% of total SOC and only reduced slowly during the almost three decades, but the implementation of this effect improved simulation results and reduced the relative RMSD (unitless) from 0.051 to 0.044 for SOC and from 0.053 to 0.049 for TN error level. From these results we conclude that the larger the SOM change the more important is the integration of the turnover of physically stabilised SOM within the modelling approach.

1. Introduction

Soil and soil functions are gaining increasing attention because healthy soil is a fundamental requirement for sustainable development. As the largest terrestrial biotic carbon pool (Stockmann et al., 2013), SOM is a particular focus of the global change debate. SOM is a driver for important soil functions like carbon storage and nutrient release. However, SOM is affected by global change due to the interactions with climate conditions and changes of land management. Therefore, modelling is widely used to predict possible impacts of land use changes on SOM storage in search for carbon sequestration strategies or adaptation measures, especially regarding agroecosystems.

Most SOM models distribute the organic matter (OM) of the soil between several conceptual pools with specific turnover times to reflect the observed SOM dynamics on long-term experiments where, in most cases only SOC is used to indicate the quantitative changes while the N component of SOM is not considered. If the turnover time of a pool is very high or tending to infinity, it may be considered as inert or more generally, as being stabilised long-term. In common agricultural systems this long-term stabilised SOC represents the basic level above which the SOC observations fluctuate, representing the dynamics of the more labile pools. On a bare fallow treatment these more labile SOM pools are continuously depleted, and the observable SOC dynamics are increasingly dominated by the properties of the stabilised SOM pools. Hence, SOC dynamics on bare fallow treatments are considered suitable to analyse the behaviour of the long-term stabilised SOM pool (Barré et al., 2010; Menichetti et al., 2015).

A special fallow experiment on a Chernozem soil was started in 1988 in Bad Lauchstädt, Germany including treatments to study the effects of keeping the soil bare by either tillage or herbicide application. The SOM data from this experiment were used to model the behaviour of stabilised SOM on these bare fallow treatments and to review the assumptions about the tillage effect on SOM turnover already implemented in the CCB model (Franko and Spiegel, 2016).

In general, the CCB model (Franko et al., 2011) considers three pools of SOM: active SOM (ASOM), stabilised SOM (SSOM), and long-term stabilised SOM (LTS). These SOM pools can be combined with different pools of fresh organic matter according to the land use. Site-specific turnover is simulated using the concept of Biologic Active Time (Franko and Oelschlägel, 1995), which is similar to the use of the site-specific rate modifier within ICBM (Introductory Carbon Balance Model) of Andrén and Kätterer (1997).

So far, the CCB model concept has considered the LTS pool as not taking part in the turnover processes. Following the concept of Kuka

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et al. (2007), the calculation of the LTS pool size is based on indicators of soil structure given by the hydrological soil characteristics such as pore volume, field capacity, and permanent wilting point (Θ_{pwp}) as reported by Puhlmann et al. (2006). These hydrological soil characteristics are influenced by soil texture, SOC concentration, and bulk density (BD). We therefore hypothesise that BD and Θ_{pwp}, which depend on soil texture and SOC, are the main drivers for changes in the LTS pool size. In many cases, these physical soil properties are handled as parameters that don't change over the investigated time. This might be reasonable when looking at short time scales and moderate SOC changes that are typical for many agroecosystems. However, this assumption is not reasonable in case of an extraordinary SOC variation after land use changes from normal agriculture to bare fallow. Despite the known dependence of BD and Θ_{pwp} from SOC (e.g. Körschens et al., 1995), it remains an open question to what degree a change of soil physical properties influences the observable SOM dynamics in terms of SOC and TN. Therefore, we included both elements (C and N) in the assessment of the model results and implemented an additional sub model in CCB that adapts BD and Θ_{pwp} to the current SOC level and changes the LTS pool size according to the actual soil physical parameters.

The objective of this study was to assess the performance of the extended CCB model to predict the dynamics of SOC and TN in general, to analyse the dimension of the modelled LTS pool change and the tillage impact on SOM dynamics under bare fallow. Furthermore, we compared our results with results from Barré et al. (2010) where the SOC under bare fallow at several sites was described by an exponential function.

2. Material and methods

2.1. Experimental design

In this study data from a field experiment situated on a Haplic Chernozem soil in Bad Lauchstädt, Central Germany (51°24′N, 11°53′E) was used. The climate is semi-humid with a mean annual air temperature of 8.9 °C and 481 mm mean annual precipitation for the last three decades.

The experiment was started in 1988 to study different fallow treatments: mechanical bare fallow (MBF) keeping the soil bare by tillage, chemical bare fallow (CBF) keeping the soil bare by herbicide application, the combination of mechanical and herbicide treatment to keep soil bare, and a zero treatment leading to a succession of weed flora. Every treatment consists of four replicated plots on a previously homogeneous managed agricultural field. Each square plot has an area of 42 m^2. For this study, only the MBF and CBF treatment were selected. The MBF was grubbed with a field cultivator several times throughout a year and ploughed every autumn to a depth of 28 cm. CBF was sprayed with herbicides (mainly triazines and glyphosate) several times a year with a knapsack sprayer to prevent any greening.

The soil texture of the experimental area was analysed in 1988 using the Köhn pipette method in accordance with DIN ISO 11277: 2002–08 (2002) to determine the soil particles < 6.3 µm, resulting in an average value of 24.3 ± 1.1 M%. The clay content of the top soil (21 M%) was resumed from a more general soil description of the Haplic Chernozem at the Bad Lauchstädt site (Altermann et al., 2005).

Soil samples were taken separately from all four replications every autumn with an auger from a depth of 0–30 cm. A mixed sample from 20 randomly chosen points per replication was analysed for SOC and TN by dry combustion using a C/H/N analyser (Vario El III, Elementar, Hanau, Germany).

2.2. Dynamics of the physically stabilised SOM

According to the CIPS (Carbon In Pore Space) model (Kuka et al., 2007) a highly stabilised SOC pool is closely associated with the inner surface of micro pores (r < 0.05 µm) in soil. Until now, CCB and its ancestor CANDY (Carbon And Nitrogen Dynamics, (Franko and Oelschlägel, 1995) have addressed this pool as being stable over long-term, assuming it as constant since change in size with time was expected to be insignificant. It is likely that this postulate is not reasonable for the time after conversion from a cropped soil with sufficient supply of organic matter into a bare fallow treatment. Thus, we considered a dynamic approach for the LTS pool in our modelling study.

Assuming that the LTS dynamic is controlled by soil physical properties, the pool size can be calculated by:

$$SOC = \alpha \bullet (A_{\mu} + A_{m} + A_{M}) \tag{1}$$

where α is the areal specific carbon concentration, A is the inner area of micro (µ), meso (m), and macro (M) pores in soil. The size of the LTS pool is given by:

$$C_{LTS} = \alpha \bullet A_{\mu} \tag{2}$$

$$C_{LTS} = SOC \bullet \frac{A_{\mu}}{A_{\mu} + A_{m} + A_{M}} = SOC \bullet F_{lts} \tag{3}$$

where F_{lts} is a soil structure depending factor relating the LTS pool size to total SOC. Further details of F_{lts} calculations were given by Kuka et al. (2007), Puhlmann et al. (2006), and Franko et al. (2011).

Using our approach, a change of the LTS pool size will be triggered by a volume change of micro pores V_{μ}. Like described in the CIPS model (Kuka et al., 2007), we associate V_{μ} with soil moisture at wilting point (Θ_{pwp}). Assuming cylindrical pores, the volume of the micro pores is related via the (virtual) radius r_{μ} and the total length l_{μ} to the inner area A_{μ} of all micro pores:

$$V_{\mu} = \Theta_{pwp} = \pi \bullet r_{\mu}^{2} \bullet l_{\mu} \tag{4}$$

$$A_{\mu} = 2 \bullet \pi \bullet r_{\mu} \bullet l_{\mu} = 2 \bullet \frac{\Theta_{pwp}}{r_{\mu}} \tag{5}$$

Additionally, it is assumed, that the long-term (physically) stabilised carbon is evenly distributed over the inner surface of the micro pores:

$$C_{LTS} = \alpha \bullet A_{\mu} = 2 \bullet \alpha \bullet \frac{\Theta_{\mu}}{r_{\mu}} = \beta \bullet \Theta_{pwp} \tag{6}$$

where β is a variable factor relating the LTS carbon to the volume of micro pores. Following Eq. (6), the changes of C_{LTS} are related to the changes of Θ_{pwp}:

$$\Delta C_{LTS} = \beta \bullet \Delta \Theta_{pwp} \tag{7}$$

The value of β in Eq. (7) is calculated during the model initialisation by

$$\beta = \frac{SOC \cdot F_{lts}}{\Theta_{pwp}}. \tag{8}$$

The implementation of this sub-routine includes the modelling of the soil physical parameters with respect to SOC changes. Therefore, we first calculated BD dynamics using the model of Rühlmann and Körschens (2009) and used the pedotransfer function of Vereecken et al. (1989) to find the parameters for the widely used water retention model of Van Genuchten (1980). This way it was possible to adapt the extension of micro pores according to the actual BD and SOC values.

2.3. Implementation of carbon and nitrogen fluxes

In the CIPS model, the carbon flux into the micro pore space is restricted to dissolved organic carbon (DOC). Any DOC production or consumption is closely related to microbial activity. The ASOM pool of the CCB model behaves very similarly to soil microbial biomass. Therefore, we assume that the flux between time step t_i and t_{i+1} to/from the LTS pool only affects the ASOM pool and hypothesise that: