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Implications of input estimation, residue quality and carbon saturation on the predictive power of the Rothamsted Carbon Model

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ABSTRACT

Effects of fertilisation and cropland management on soil organic carbon (SOC) dynamics can be assessed best in long-term experiments. Using data from the long-term fertilisation experiment in Puch, Germany (part of the series "Internationale Organische Stickstoff Dauerversuche", IOSDV), we tested the performance of the Rothamsted Carbon Model 26.3 (RothC). The objectives of this work were: (i) quantify the C-input and the efficiency of SOC stabilisation, (ii) test the performance of different input estimates on predictive power of the RothC and (iii) test implementations of residue quality and C-saturation on model predictions. The experiment is a full-factorial strip design, the factors being "organic amendment" and "level of N-fertiliser". Each treatment was replicated three times. The crop rotation is silage maize–winter wheat–winter barley. Five levels of the factor "organic amendment" were considered: (i) CON: no organic amendment; (ii) SLU: slurry application (on average 0.8 Mg C ha^{-1} $year^{-1}$); (iii) FYM: application of farmyard manure (30 to 40 Mg ha^{-1} fresh mass every third year to maize, on average 1.0 Mg C ha^{-1} $year^{-1}$); (iv) STR: straw incorporation after harvest of wheat and barley (depending on straw yield on average 0.7 to 2.2 Mg C ha^{-1} $year^{-1}$); (v) STSL: slurry application plus straw incorporation (on average 1.1 to 2.4 Mg C ha^{-1} $year^{-1}$). All treatments (including CON) were combined with five different levels of N-fertilisation (N0 to N4), whereas N0 was nil N application and N4 averaged 177 kg N ha^{-1} $year^{-1}$. N-rates increased gradually and differed depending on the crop. Starting values for SOC stocks (Mg ha^{-1}) were measured in 1983 as a mean among N-rates for organic amendment treatments (CON: 42; SLU: 39.8; FYM: 40.5; STR 39.8; STSL: 40.5). SOC stocks (0–25 cm) in 2004 (35.5 to 46.6 Mg C ha^{-1}) were in the order STSL > FYM = SLU > STR = CON ($p \leq 0.001$). However, slightly different starting values indicated a higher loss of SOC after 21 years in the CON (11–14%) compared to the STR treatments (1–10%). Effect of N-rate was not significant. The observed relation between change of SOC and C-input was quadratic ($Y_O = -13.4 + 7.5x - 0.9x^2$; $R^2 = 0.74$, $p \leq 0.001$), which contrasted the linear relationship predicted by RothC ($Y_P = -12.9 + 5.5x$; $R^2 = 0.97$, $p \leq 0.0001$). Serious deviation between observed and predicted relationship occurred above C-inputs of 2.5 Mg C ha^{-1} $year^{-1}$. Mechanistic explanation (e.g. C-saturation or increased mineralisation by N-fertilisation) for the observation needs further exploration, but implication on regional estimates for C-accumulation for different cropland management scenarios is obvious: potential gain in SOC storage by increasing C-inputs may be overestimated, at least under conditions of the Puch site. Independent model predictions (i.e. no parameter adjustment and independent estimation and measurement of C-input) were successful for treatments without straw incorporation (CON, SLU, FYM). Using a regression between crop yields and crop residue input yielded better results than using a constant belowground-to-aboveground biomass ratio. SOC stocks of treatments STR and STSL were seriously overestimated by the model. Using a higher decomposability of crop residue improved result only marginally and required the change of a standard parameter. Using a simple implementation of C-saturation improved predictions for STR and STSL but failed to simulate dynamics in all other treatments. Overall, our results showed that it is important to recognise that relation between SOC change and C-input is not necessarily linear. However, the RothC model predicted SOC dynamics well at lower input levels. Observation that a regression equation for input estimation is superior to a constant biomass ratio for modelling purposes has to be tested further. An implementation of residue quality or saturation capacity in the RothC model may be promising for a better mechanistic understanding of SOC dynamics. However, this requires careful calibration and will increase the number of parameters to be fitted.

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1. Introduction

Soil organic carbon (SOC) is an important compartment of the global carbon cycle. SOC in cropland is a potential source or sink for CO_2, thereby affecting climate and food security (Lal, 2004; Paustian et al., 2000). Models simulating SOC dynamics may be useful to quantify changes in SOC due to general land use change (Gonzalez-Molina et al., 2011), cropland management such as fertilisation and organic amendment (Ludwig et al., 2010; Paustian et al., 1992; Powlson et al., 2011) and to deepen understanding on C-sequestration processes (Henriksen and Breland, 1999; Leifeld et al., 2008; Ludwig et al., 2007).

Independent prediction of SOC dynamics is an ultimate aim in modelling. Independent prediction means a successful modelling of "true" SOC stocks without often used site-specific calibration or optimisation of model or input parameters. Successful modelling of SOC stocks after land-use or cropland management changes have been reported often with the Rothamsted Carbon Model "RothC-26.3" (e.g. Guo et al., 2007; Skjemstad et al., 2004; Smith et al., 1997; Todorovic et al., 2010). However, optimised C-inputs (i.e. amount of input was iteratively changed to match observed data) were used (Guo et al., 2007; Smith et al., 1997) or decomposition constants were changed (Skjemstad et al., 2004; Todorovic et al., 2010). Alternatively, the amount of IOM (inert organic matter, Fig. 1) can be optimised to match observed SOC stocks (Ludwig et al., 2010). For independent predictions no further parameterisation and a reliable estimate of C-input into the soil is preferable.

A common approach to estimate C-input is to assume a certain ratio between belowground biomass (BGB) and aboveground biomass (AGB) (Lugato et al., 2006; Skjemstad et al., 2004). AGB in cropland soils most often increases with fertiliser rates, but root growth is not necessarily proportional. This may result in a decreasing BGB-to-AGB ratio. Consequently, better predictions were achieved by using an empirically derived regression equation (Eq. (1)) between crop yields and residue input (Ludwig et al., 2007, 2010). The equation, originally developed by Franko (1997), still has to be tested on more sites with the RothC model.

Not only amount but quality may influence decomposition of crop residue (Paustian et al., 1997a). This was implemented into the RothC model by the DPM-to-RPM ratio (decomposable plant material-to-resistant plant material ratio), which is normally only altered between different land-use types (Coleman and Jenkinson, 1999). However, Ludwig et al. (2007) concluded that changing the DPM-to-RPM ratio had only minor effects on modelled C-stocks in an experiment at Bad Lauchstädt. This may be explained by the function of the model: decreasing the decomposability of C-input mainly leads to higher stocks in the RPM, but not in the HUM (humified organic matter) pool (Paustian et al., 1997a).

Greater deviations from predictions and observations may occur when essential assumptions underlying the RothC model (and most other models) are wrong. That is, if deviations from first order kinetics decay of the pools occur. In some long-term experiments no further increase in SOC stocks were observed despite higher C-inputs (Chung et al., 2010; Gulde et al., 2008; Paustian et al., 1997b). This may be explained by the theory of C-saturation of the whole soil or some fractions (Hassink and Whitmore, 1997; Stewart et al., 2007). Relationship between C-input and SOC level is assumed not to be linear but to asymptotically approach a maximum level (Six et al., 2002; West and Six, 2007). C-saturation implies that stabilisation efficiency of C-inputs (at steady state) depends on the C-saturation deficit, i.e. C-input is less effective in increasing SOC stocks at higher levels.

A long-term experiment was established in Puch, Germany in 1983 as part of a whole experimental series ("Internationale Organische Stickstoff DauerVersuche", IOSDV) all over Europe. The aim of the experiment was to test interactive effects of organic amendments (straw incorporation, farmyard manure, slurry) and N-fertiliser rates on agronomic parameters and SOC. Prior measurements of SOC contents revealed only minor differences between most treatments (Diez et al., 1997; Hege and Offenberger, 2006), but the range of C-inputs was not systematically assessed until now and the dataset was neither explored intensively (in relation to SOC dynamics) nor used for model evaluation. Objectives of this work were to (i) quantify the C-input and the efficiency of SOC stabilisation, (ii) test the performance of different input estimates on predictive power of the RothC-26.3 model and (iii) test implementations of litter quality and C-saturation on model predictions.

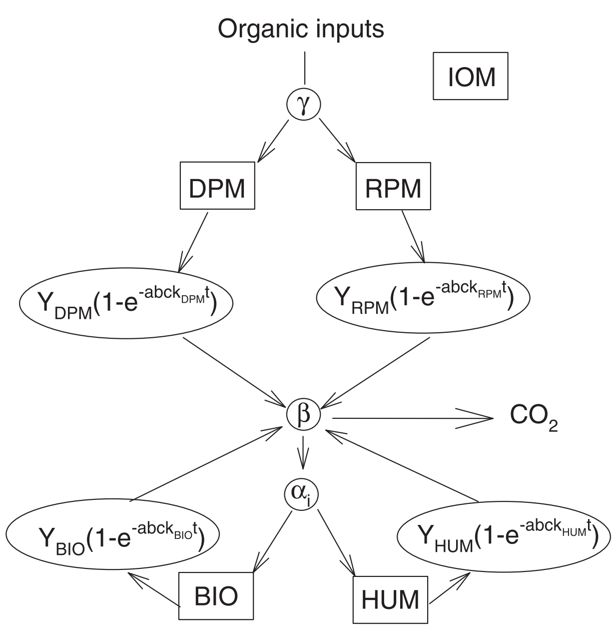

Fig. 1. Structure of the RothC-26.3 model (Coleman and Jenkinson, 1999). Pools (squares) are DPM (decomposable plant material, $k_{DPM} = 10\ year^{-1}$), RPM (resistant plant material, $k_{DPM} = 0.3\ year^{-1}$), BIO (microbial biomass, $k_{DPM} = 0.66\ year^{-1}$), HUM (humified organic matter, $k_{DPM} = 0.02\ year^{-1}$) and IOM (inert organic matter, no decomposition assumed). *Yi* is the amount of decomposed C in pool *i* with the rate constant *k*. *k* is modified by temperature *a*, moisture *b*, soil cover *c* and time *t*. Three partitioning coefficients exist: γ is the coefficient of organic inputs into DPM and RPM (standard for cropland: 59% DPM and 41% RPM); β alters the partitioning between CO_2 evolved and HUM + BIO formed and is modified by clay content. αi is the amount of BIO + HUM partitioned into BIO (α_{BIO}, 46%) or HUM (α_{HUM}, 54%). Note that α_{BIO} and α_{HUM} were modified by Eq. (2a–c) in model version C and γ was changed in model version C.

2. Material and methods

2.1. Site description

The site is located in Puch, Germany near to the city of Munich (48°11′ N, 11°12′ E). Mean annual temperature from 1984 to 2009 was 8.4 °C and mean annual precipitation was 868 mm $year^{-1}$. The soil was classified as Luvisol (WRB, 2007) derived from loess sediments (clay: 18%, silt: 73%, sand: 9%) with pH values below 6.5 in 1983 and around 6.2 in 1994 (Diez et al., 1997). Bulk density was estimated to 1.5 g cm^{-3} in the plough layer (25 cm). The site was used as cropland before, presumably for decades or centuries. Before starting the experiment, soil samples (0–25 cm) were taken for plots receiving different organic amendments, but bulked across replicates and N-rates (see below). Therefore, different amounts of SOC were calculated for different organic treatments in 1983 (see Table 2, Fig. 3). Soil samples (8–10 cores per plot) for SOC measurements by dry combustion (Leco RC 512, Leco Corporation, St. Joseph, MI, USA) were taken from N0, N2 and N4 treatments and were bulked across replicates in 1986, 1989 and 2003. In 1994 and 2004 all treatments