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RothC simulation of carbon accumulation in soil after repeated application of widely different organic amendments

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ABSTRACT

Multi-compartment soil carbon (C) simulation models such as RothC are widely used for predicting changes in C stocks of arable soils. However, rigorous routines for establishing entry pools that account for the diversity of exogenous organic matter (EOM) applied to croplands are still lacking. We obtained data on changes in soil C stocks after repeated applications of EOM from four long-term experiments (LTEs): Askov K2 (Denmark, 31 yrs), Qualiagro (France, 11 yrs), SERAIL (France, 14 yrs) and Ultuna (Sweden, 52 yrs). The adjustment of the partition coefficients of total organic C in EOM (EOM-TOC) into the labile, resistant and humified entry pools of RothC (f_{DPM}, f_{RPM}, f_{HUM}, respectively) provided a successful fit to the accumulation of EOM-derived C in the LTE soils. Equations estimating the EOM partition coefficients in the RothC model were based on an indicator (I_{ROC}) of the EOM-TOC potentially retained in soil. I_{ROC} was derived from the C found in the soluble, lignin + cutin-like and cellulose-like Van Soest fractions and the proportion of EOM-TOC mineralized during 3 days of incubation. Using the EOM partition coefficients derived from these laboratory analyses resulted in RothC simulations with only slightly larger errors than simulations based on partition coefficients fitted from LTE soil data, except for EOMs that caused very large accumulations of C in soil (e.g. peat) possibly due to factors not accounted for in the RothC model, such as change in soil pH. The proposed partitioning of EOM-TOC allows the potential soil C storage after EOM applications to be predicted regardless of field location and specific composition of EOMs.

1. Introduction

Loss of soil organic C (SOC) may lead to reduced soil fertility and increased soil erosion (Matson et al., 1997; Ciais et al., 2010). The loss of SOC has been identified as a major threat towards the soil resource (European Commission, 2006), and small but consistent increases in SOC could mitigate climate change effects by storing atmospheric CO_2–C (Lal et al., 2007).

Annual application of exogenous organic matter (EOM) to cultivated land may lead to long continued accumulation of SOC (Marmo et al., 2004). We define EOM as crop residues, animal manures, and organic wastes from urban areas, forestry and industry as these materials are subject to similar transformations in soil and to similar management methods (Marmo et al., 2004). In Europe, recycling of biodegradable wastes is expected to increase in the future (European Commission, 2010). Different EOMs differ in their potential contribution to SOC, depending on their origin and degree of transformation before being added to soil (Christensen and Johnston, 1997; Gerzabek et al., 1997; Bipfubusa et al., 2008). Since C stocks change slowly, long-term field experiments are needed to evaluate the effects of repeated applications of EOM (IPCC, 1997).

Multi-compartment models of C turnover in soil (Jenkinson and Rayner, 1977; Parton et al., 1987; Andren and Kätterer, 1997; Bruun et al., 2003) accurately simulate SOC dynamics in long-term field experiments under different climatic conditions and soil types (Smith et al., 1997b). RothC is one of the most widely used model that simulates SOC dynamic based on relatively few parameters and input data. In RothC, total organic C in EOM (EOM-TOC) is distributed into pools of labile (DPM), resistant (RPM) and humified

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(HUM) organic matter by partition coefficients (f_{DPM}, f_{RPM} and f_{HUM}, respectively). The RothC model was initially calibrated with results from several Rothamsted long-term experiments leading to partition coefficients for crop residues (f_{DPM} = 59% and f_{RPM} = 41% of EOM-TOC) and farmyard manure (FYM; f_{DPM} = 49%, f_{RPM} = 49% and f_{HUM} = 2% of EOM-TOC) (Coleman and Jenkinson, 1999). Such partitioning has frequently been used to simulate the effect of agricultural management (e.g. manure application) on changes in SOC stocks (Coleman et al., 1997; Yokozawa et al., 2010). In some studies, partition coefficients for manure are not specified (Falloon and Smith, 2002; Yang et al., 2003; Guo et al., 2007) or are modified without proper documentation (Kamoni et al., 2007). A range of EOMs with contrasting chemical composition and decomposability have been applied to soil (Thuriès et al., 2002; Lashermes et al., 2009) and specific partition coefficients have been used to simulate changes in SOC under different farming systems (Leifeld et al., 2009). Establishing RothC partition coefficients based directly on analytical characteristics of the applied EOMs would facilitate the simulation of long-term changes in SOC after successive applications of EOM.

In the CENTURY model, EOM-TOC is split into metabolic and structural pools based on the lignin:N ratio (Parton et al., 1987), while in the STICS model, the behaviour of plant residues is based on their C:N ratio (Nicolardot et al., 2001). However, these approaches have been shown to be inadequate to simulate changes in SOC in long-term experiments with manure application (Kamoni et al., 2007) and have not been tested for EOMs such as composts and sludge. The stabilization of N in composts changes the biological meaning of the C:N ratio (Paré et al., 1998). Moreover, the lignin content may not represent the recalcitrant fraction of composted EOM because lignin is partly degraded during composting while other recalcitrant compounds are formed and recovered in soluble forms (Morvan and Nicolardot, 2009; Peltre et al., 2010). Thus, Hyvönen et al. (1996) argued that the lignin in EOM was not a valid indicator of EOM quality in a model of continuous quality distribution of soil organic matter.

Lashermes et al. (2009) developed an indicator of the fraction of EOM-TOC that potentially is retained in soil in the long-term (I_{ROC}). The I_{ROC} indicator is calculated from analytical characteristics of the EOM and has been calibrated against long-continued C mineralization kinetics in laboratory incubations for a wide range of EOMs including plant materials, animal manures and various types of fresh or composted wastes. We surmise that this indicator can be used to estimate the partition of EOM-TOC in the RothC model.

Our objective was to devise a method to establish the partition coefficients of EOMs in the RothC model based on analytical characteristics of EOMs. We first ran the model to reproduce the accumulation of EOM-derived C in soil by simulating the additional C in amended plots compared to un-amended reference plots in four long-term field experiments. We adjusted the partition coefficients of the RothC entry pools for contrasting EOMs applications to fit the changes in EOM-derived soil C. Then we developed equations to derive the partition coefficients of EOMs in RothC entry pools from their chemical composition. Finally, we tested the feasibility of simulating the accumulation of EOM-derived C in soil when using the RothC partition coefficients derived from laboratory analyses.

2. Materials and methods

2.1. Field experiments

Data was assembled from four differently sited long-term field experiments (LTEs) where various types of EOMs had been applied regularly. The LTEs differed in their soil types, climatic conditions and management. The LTEs were the Askov K2 (Christensen and Johnston, 1997), Qualiagro (Houot et al., 2002), SERAIL (Berry et al., 2008) and Ultuna (Gerzabek et al., 1997). Table 1 summarizes selected characteristics of the LTEs, including average climatic data, initial soil characteristics, crop rotation and EOM applied.

2.1.1. The Askov K2 experiment

The Askov K2 experiment was situated at Askov Experimental Station, Denmark. The soil was retrieved from the 50–100 cm soil depth and adopted as topsoil in large concrete cylinders (diam. 0.986 m; area 0.76 m^2; depth 0.50 m). The depth of the soil layer amended with EOM (0–25 cm) was delineated by a coarse-meshed net to ensure a constant amount of soil into which the EOM was incorporated and from which soil samples were taken. The experiment grew a four-course crop rotation that received annual applications of 4 different EOMs (Table 1): physiologically mature cereal straw (STR-Ask), sawdust (SAW-Ask), dry FYM (FYM-Ask) and white sphagnum peat (PEA-Ask). Each treatment was in two replicates and reference plots without EOM amendment were included. All plots received additional mineral N fertilization to ensure similar crop production in all treatments. At harvest, all above-ground plant parts were removed, leaving 4 cm of stubbles. Soils were sampled from 0 to 25 cm soil depth every four years and analysed for C content. A soil bulk density of 1.5 Mg m^{-3} was adopted (Bruun et al., 2003). Further details of the experiment are given by Christensen and Johnston (1997).

2.1.2. The Qualiagro experiment

The ongoing Qualiagro experiment, located in Feucherolles, near Paris, France, was initiated in 1998. It is cropped with a maize-wheat rotation and includes 4 EOM treatments and a reference with no EOM application. EOMs are applied every second year on wheat stubbles using 10 × 45 m^2 plots separated by 6 m wide strips. The EOMs include a municipal solid waste compost obtained by composting solid municipal wastes after removal of its content of dry and clean packaging (MSW-Qua), an FYM (FYM-Qua), a compost derived from co-composting green wastes with sewage sludge (GWS-Qua), and a biowaste compost produced by co-composting green wastes with a source-separated organic fraction of municipal solid wastes (BIOW-Qua). Two mineral N fertilization regimes (optimum and minimum mineral N fertilization, referred as +N and −N, respectively) are applied on all organic treatments in two separate sections of the field experiment. Within each N fertilization regime, the EOM treatments occur in a randomized block design with four blocks placed 25 m apart to prevent cross-contamination during EOM applications. Annual dry matter yields of grain and plant residues are determined manually before harvest. In 2007, barley was grown due to prognoses of a regional attack of *Diabrotica virgifera* to maize, causing EOMs to be applied in two consecutive years (2006 and 2007). Soil is sampled late August from the topsoil (0–29 cm) prior to EOM application and analysed for C content. Topsoil bulk density was measured plot-wise in 1998 (start of the experiment), 2004 and 2009. Additionally, bulk density and C content of the subsoil (29–35 cm) was measured in September 2004.

2.1.3. The SERAIL experiment

The ongoing SERAIL experiment, located in Brindas, near Lyon, France, was started in 1995. The soil is under a rotation of vegetables (lettuce, turnip, spinach, leek, carrot, cabbage, Swiss chard, celery). Five different EOMs are applied annually: dried FYM (FMT-Ser), fresh FYM (FYM-Ser), enriched bark compost produced by co-composting bark with poultry manure, liquid manure and algae (ALG-Ser), compost produced by co-composting coffee cake (90%), sheep manure and wool waste (VGH-Ser), and a green waste