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The relative importance of decomposition and transport mechanisms in accounting for C profiles

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Abstract

Soil is the major terrestrial reservoirs of carbon, and a substantial part of this carbon is stored in deep layers, typically deeper than 50 cm below the surface. Several studies underlined the quantitative importance of this deep Soil Organic Carbon (SOC) pool and models are needed to better understand this stock and its evolution under climate and land-uses changes. In this study, we test and compare 3 simple theoretical models of vertical transport for SOC against SOC profiles measurements from a long-term bare fallow experiment carried out by the Central-Chernozem State Natural Biosphere Reserve named after V.V. Alekhin, in the Kursk Region of Russia. The transport schemes tested are diffusion, advection or both diffusion and advection. They are coupled to two different formulations of soil carbon decomposition kinetics. The first formulation is a first order kinetics widely used in global SOC decomposition models; the second one links SOC decomposition rate to the amount of fresh organic matter, representing a "priming effect". Field data are from a set of three bare fallow plots where soil received no input during the past 20, 26 and 58 yr respectively. Parameters of the models were optimized using a Bayesian method. The best results are obtained when SOC decomposition is assumed to be controlled by fresh organic matter. In comparison to the first-order kinetic model, the "priming" model reduces the underestimation of SOC decomposition in the top layers and the over estimation in the deep layers. We also observe that the transport scheme that improved the fit with the data depends on the soil carbon mineralization formulation chosen. When soil carbon decomposition is modelled to depend on the fresh organic matter amount, the transport mechanisms which improves best the fit to the SOC profile data is the model representing both advection and diffusion. Interestingly, the older the bare fallow is, the lesser the need for diffusion is. This suggests that stabilized carbon may not be transported within the profile by the same mechanisms than more labile carbon.

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1 Introduction

Soils are the major reservoir of continental organic carbon (C) representing more than twice the amount of C stored in the atmosphere and three times the amount of C stored in terrestrial vegetation (Schimel, 1995; Schlesinger, 1990; MEA, 2005). In spite of the importance of the stock, the dynamics of soil C is not deeply understood (Sugden et al., 2004). Soil scientists have mainly focused on the first soil layers (Lueken et al., 1962; Sparling et al., 1982; Wu et al., 1993), considered to be the only region of the soil which can emit CO_2 to the atmosphere in significant amounts. However, recent studies have shown that the amount of C stored in the deep layers (below 30 cm) could represent between 30 and 63 % of the total amount of soil C (Batjes, 1996; Jobbagy and Jackson, 2000; Tarnocai et al., 2009). Consequently, an increasing attention has been paid to deep soil C and in particular to its dynamics (Fontaine et al., 2007; Salomé et al., 2010; Rumpel et al., 2010; Sanaullah et al., 2010).

Transport mechanisms of soil C into deep layer is still not well understood. The models applied at site-level generally represent both vertical advection and diffusion (Elzein and Balesdent, 1995; Bruun et al., 2007; Braakhekke et al., 2011) but models also exist with only advection (Feng et al., 1999; Dörr and Münnich, 1989; Jenkinson and Coleman, 2008) or only diffusion (O'Brien and Stout, 1978; Wynn et al., 2005). To our knowledge, no clear comparison of those three transport schemes has been performed, even if Bruun et al. (2007) suggested that the representation of both advection and diffusion mechanisms improved their model for a sandy soil. However, they compared a model with both advection and diffusion to an advection-only model but they do not compare these models with a diffusion-only model.

The Soil Organic Matter (SOM) decomposition mechanisms proposed as equations that can be encapsulated in models are also very diverse (for review see, Manzoni and Porporato, 2009; Wutzler and Reichstein, 2008). Within all these approaches, the most used formulation is the first order kinetics as in the CENTURY (Parton et al., 1988) or in RothC (Coleman and Jenkinson, 1996). In this formulation, the decay of each

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SOM pool during two consecutive time steps is proportional to the pool's size, thereby considering no interactions between two decomposing pools.

In particular, within the fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), the climate-carbon models used during the Coupled Carbon Cycle Climate Model Intercomparison Project(C^4MIP) represented the SOM decomposition with first order kinetics (Friedlingstein et al., 2006). This approach is now criticized (Fontaine and Barot, 2005; Wutzler and Reichstein, 2008) in particular for its incapability to represent the relationship existing between Fresh Organic Matter (FOM) inputs (e.g. roots exudates, litter, etc.) and the mineralisation of the SOM. This interaction seems to be a major mechanism of SOM stabilization in the deep soil layers (Fontaine et al., 2007) even if it could be soil dependent (Salomé et al., 2010). However, here again, to our knowledge no clear comparison between first order kinetics and any of the alternative decomposition formulations linking FOM input to SOM mineralisation has been done.

To study how FOM may possibly interact with SOM mineralization, experimental sites such as long-term bare fallow soils are interesting experiments. Instead of the complexity of real soils where FOM is permanently added and depends on ecosystem properties, in a bare fallow, the input of FOM has just been stopped for years. Consequently, the relationship between FOM input and SOM mineralisation is switched-off in the bare fallow, whereas it remains switched on in the control plot.

In this study, we develop a suite of conceptual models to compare the three main transport schemes (advection only A; diffusion only D, both together AD) proposed in the literature using measurement of soil C profiles obtained in a long-term bare fallow and a control plot near Kursk in Russia. We also aim to cross the 3 transport schemes with the 2 different formulations used to describe SOM mineralisation (first order kinetics without relationship between FOM input and SOM mineralisation and a formulation inspired from Wutzler and Reichstein (2008) where the relationship between FOM input and SOM mineralisation (priming effect) is represented). We first optimize the parameters of each of the 6 possible models, using few observed soil carbon profiles and

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a statistical optimization method (least square minimization). We then compare the model outputs with measurements from all soil carbon profiles from the bare fallow.

2 Materials and methods

2.1 The Kursk long-term field experiment data

2.1.1 Site and soil plots description

Soils were sampled at the long-term field experiment the Central-Chernozem State Natural Biosphere Reserve named after V.V. Alekhin in the Kursk Region of Russia. The climatic zone is a forest steppe temperate, moderately cold with a mean annual precipitation of 587 mm and a mean annual air temperature of 5.4 °C (Central-Chernozem State Natural Biosphere Reserve, 1947–1997). The soil is a Haplic Chernozem defined as a silty loam Haplic Luvisol following the FAO classification. Two long-term plots were sampled within the site located in the Streletskyi section of the reserve at 51° N, 36° E, about 18 km south of the city of Kursk (Vinogradov, 1984).

The first plot is a long-term bare fallow soil (LTBF) where no fresh input entered into the soils since 1947. The soil was tilled every year by horse traction at a depth corresponding to 17–18 cm until the middle of the 1970's and then using machine at a depth of 22–24 cm. Before the start of the experiment, the soil was under a natural steppe that had been under hay-harvest and pasture for at least the last four centuries. The second plot is geographically close to the first one (about 50 m). It is the same natural steppe that has been absolutely reserved since the establishment of the Reserve in 1935 (Afanasyeva, 1966). It is a natural steppe since 1935 and was used before for pasture. Dominant plant species are meadow bromegrass (*Bromus riparius* Rehm.), wild oats (*Stipa pennata* L.), narrow-leaved meadow grass (*Poa angustifolia* L.), intermediate wheatgrass (*Elytrigia intermedia* (Host) Nevski), meadowsweet rose

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(*Filipendula vulgaris* Moench), and green strawberry (*Fragaria viridis* Duch.). This soil can be considered as a control (undisturbed) plot for the LTBF experiment.

A compaction of the LTBF soil is observed on the site, leading to 10 cm difference between the deepest studied horizon of the control and the one of the LTBF. To take into account the compaction effect on soil depth, we define the point at 0m depth as the floor of the steppe and then the soil layers were assumed to be linearly compacted through time since 1947 to reproduce the observed final difference of 10 cm between the two bottom horizons.

2.1.2 Soil sampling and carbon measurements

Soils were sampled at the LTBF plot in 1967, 1973 and 2005 at depths of every 10 cm down to 150 cm. The soil of the steppe was sampled in 2006 at depths of every 10 cm down to 150 cm. Soils were sampled five times in the steppe, in the bare fallow in 1967 and 2005 and three times in 1973. The corresponding profiles are hereafter called 20YBF, 26YBF and 58YBF for the bare fallow soil sampled in 1967, 1973 and 2005, respectively (i.e. after 20, 26 and 58 yr of bare fallow) and S for the steppe. C contents obtained by the Tyurin method in 1967 and 1973 are corrected by a multiplicative factor 1.13, determined particularly for this soil to match dry combustion method and thus avoid any underestimation of the C content (Vasilyeva, personal communication, 2012). In years 2005 and 2006, soil C was measured by dry combustion (Vario Elementar, Analysensysteme, Hanau, Germany).

The bulk density of the soils was first measured for each layer until 120 cm depth in 1959, and this measurement was repeated in 2002 for the bare fallow and for the steppe plots. To take into account the difference in bulk density between the samples, the C stocks are expressed in $\mathrm{t\,C\,ha^{-1}}$ as follows:

$$\mathrm{Cstock} = \mathrm{TOC} \times \mathrm{BD} \times h \tag{1}$$

With TOC being the total organic carbon content of the layer considered, expressed in $\mathrm{g\,C\,g^{-1}}$ soil, BD the bulk density expressed in $\mathrm{g\,soil\,cm^{-3}}$ and h the layer height

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expressed in cm. The bulk densities measured in 1959 are used for the soil layer sampled in 1967 and in 1973, whereas the bulk densities measured in 2002 are used for the soil layers sampled in 2005 and in 2006.

2.2 The different soil carbon decomposition models tested

The models tested here against observations split the total OM in two pools, the FOM and the SOM for each soil layer (Fig. 1). Input to the FOM pool comes from plant litter and the distribution of this input within the profile is assumed to depend upon depth from the surface (z) according to a negative exponential function, in order to represent the decreased injection of FOM from root mortality with increasing z. This is given by the equation:

$$I(z) = I \times \exp(-\mu \times z)/\Sigma \exp(-\mu \times z) \quad (2)$$

Where $I(z)$ defines the input of FOM at depth z, I is a scalar corresponding to the total input of carbon. We use $I = 34\,\mathrm{t\,C\,ha^{-1}}$ which is the mean of the C input over the period 1954–1961 for the steppe considered in this study (Afanasyeva, 1966). μ is a parameter describing the exponential of FOM input from root mortality (or exudates) in the vertical profile.

Plant litter production is considered as constant and does not depend on climatic forcing. FOM mineralization is assumed to be governed by first order kinetics, being proportional to the FOM pool, as given by:

$$\mathrm{dFOM}/\mathrm{d}t = -k_{\mathrm{FOM}} \times \mathrm{FOM} \quad (3)$$

where FOM is the FOM carbon pool and k_{FOM} is a scalar defining its decomposition rate. A fraction of decomposed FOM is respired as CO_2 (r), another fraction is humified (e), and the rest is not decomposed to represent the protection process in particular

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the inaccessibility of FOM for decomposers (Fig. 1).

$$\text{Respired FOM} = r \times \text{dFOM}/\text{d}t \tag{4}$$

$$\text{Humified FOM} = e \times \text{dFOM}/\text{d}t \tag{5}$$

For other fluxes, we test 6 different model formulations, resulting from the combination of two formulations to describe SOM mineralization (FS), with three formulations to describe the vertical transport of carbon (T).

2.2.1 Formulation FS1

The mineralization of SOM is assumed to follow a first order kinetics, depending only on the SOM amount, as given by:

$$\text{dSOM}/\text{d}t = -k_{\text{SOM}} \times \text{SOM} \tag{6}$$

where SOM is the SOM carbon pool, and k_{SOM} its decomposition rate.

2.2.2 Formulation FS2

The mineralization of SOM depends on decomposers activity, and therefore is sensitive to FOM availability, according to:

$$\text{dSOM}/\text{d}t = -k'_{\text{SOM}} \times \text{SOM} \times (1 - \exp(-c \times \text{FOM})) \tag{7}$$

where k'_{SOM} is a SOM decomposition rate, and c a parameter controlling the importance of the FOM carbon pool in the SOM mineralization. Equation (7) is inspired from Wutzler and Reichstein (2008) who used $\text{dSOM}/\text{d}t = -k''_{\text{SOM}} \times \text{SOM} \times (1 - \exp(-c \times \text{MB}))$ but unlike in their study, we do not explicitly represent microbial biomass, the MB term in Wutzler and Reichstein (2008) and rather we use a direct relationship between SOM mineralization and FOM stock.

The three different formulations of C transport are based on an advection equation (T_{A}) or on Fick's law of diffusion (T_{D}) or on both transport mechanisms as defined by Elzein and Balesdent (1995) (T_{AD}).

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2.2.3 Formulation T_A

Advection is defined by:

$$F_A = A \times C \quad (8)$$

where F_A is the flux of C transported downwards by advection, A the advection rate ($mm\,yr^{-1}$).

2.2.4 Formulation T_D

The Fick's law is defined by:

$$F_D = -D\partial C/\partial z \quad (9)$$

where F_D is the flux of C transported downwards by diffusion, $-D$ the diffusion coefficient ($cm^2\,yr^{-1}$) and C the amount of carbon in the pool subject to transport (FOM or SOM).

2.2.5 Formulation T_{AD}

Finally, advection and diffusion are represented following the scheme of Elzein and Balesdent (1995)

$$F_{AD} = F_A + F_D \quad (10)$$

$$F_{AD} = A \times C - D\partial C/\partial z \quad (11)$$

where F_{AD} is the flux of C transported downwards by advection and diffusion, A the advection rate ($mm\,yr^{-1}$), $-D$ the diffusion coefficient ($cm^2\,yr^{-1}$) and C the amount of carbon in the pool subject to transport. We finally build the six different models by forming each possible pair of (FS, T) formulations as illustrated by Fig. 2. All the models run at a yearly time step and the vertical resolution is 5 mm.

2.3 Parameter optimization

The 9 parameters used for each simulation are listed in Table 1. Six of them are optimized for each model using a Bayesian inversion method with priors (see Tarantola, 1987) against the data collected in the LTBF after 58 yr (58YBF) and the steppe profiles (24 data points (12 for each profiles)), with a statistical approach based on a Bayesian framework (Tarantola, 1987). We use these two profiles to optimize the model because they are the most contrasted and to use both the initial condition and the final step for all runs. The optimization assumes that the errors associated to the model parameters and the observations can be described with Gaussian Probability Distribution Function (PDF). It makes use of prior information on the parameters, minimizing an objective function that measures the distance between modelled and observed carbon vertical profiles and between prior and optimized parameter values (using a least square approach). The optimized parameters (Table 1) are the SOM decomposition rate (k_{SOM}), the exponential rate parameter of FOM input from root mortality in the vertical profile (μ), the fraction of SOM mineralized recycled in FOM (e), the Fick's coefficient in models using T_{D} or T_{AD} (D), the advection rate in models using T_{A} or T_{AD} (A), and the parameter controlling the FOM dependency of the SOM mineralization in models using FS2 (c). Prior estimates for each parameter are given on Table 1. We use such values as prior because they are in the same range than parameters already published (Baisden et al., 2002; Bruun et al., 2007; Braakhekke et al., 2011). We choose prior errors of 100 % for each parameter in order to let them adjust as freely as possibly to the data. As for the observation error, note that with our formalism it should include both the measurement error and the model error. Given that only the measurement part could be estimated from the existence of several replicates for each profile, we choose an ad hoc approach with a fixed value for all observations (50 %) in order to fulfil some statistical hypothesis behind the optimization scheme: twice the cost function at its minimum should be close to the number of observations (reduced chi-square of one).

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Note finally that all errors (on the parameters and the observations) are assumed to be uncorrelated

2.4 Comparison of model results with data

C stock measured and modelled for each soil layer are compared using statistical indicators developed first by Kobayashi and Salam (2000) and then improved by Hugh et al. (2003). These statistical indicators are the Mean Square Deviation (MSD), the Squared Bias (SB), the Non-Unity slope (NU) and the Lack of Correlation (LC).

$$MSD = \Sigma(m-o)^2/n \tag{12}$$

with o the observed values, m the C stock calculated by the model and n the number of observations.

Then MSD is decomposed into three additive components following Hugh et al. (2003): the Squared Bias (SB), the Non-Unity slope (NU) and the Lack of Correlation (LC).

$$SB = (\overline{m}-\overline{o})^2 \tag{13}$$

$$NU = (1-\Sigma(m-\overline{m})\times(o-\overline{o})/\Sigma(m-\overline{m})^2)^2 \times \Sigma(m-\overline{m})^2/n \tag{14}$$

$$LC = (1-(\Sigma(m-\overline{m})\times(o-\overline{o}))^2/(\Sigma(o-\overline{o})^2\times\Sigma(m-\overline{m})^2))\times(\Sigma(o-\overline{o})^2/n \tag{15}$$

SB provides information about the mean bias of the simulation from the measurement, NU indicates the capacities of the model to reproduce the magnitude of fluctuation among the measurements (the standard deviation) and LC is an indication of the dispersion of the point over a scatterplot (the shape).

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3 Results

3.1 The representation of SOM decomposition

Figure 3 describes the MSD, SB, NU and LC statistical indicator values obtained by each different model for the entire dataset, or for each site. When MSD is calculated for the entire dataset, we generally observed a better agreement between the data and those models where SOM decomposition is controlled by FOM (FS2). This improved agreement is due to a reduction of the SB and NU values for T_A and for T_{AD}. For T_D, despite the FS2 did not reduce the MSD values we also observe a reduction of the SB when FS2 is used. It suggests that, depending on the transport formulation used, the representation of the dependency of SOM decomposition upon FOM (priming) helps to reduce the standard deviation and the mean bias. This is particularly the case for the young bare fallow plots, where better agreements with the data are always obtained in models where SOM mineralization is controlled by FOM (FS2). The magnitude of this structural improvement when "priming" is introduced in a model is particularly important when advection or both advection and diffusion are represented (Fig. 3). In these cases, the representation of "priming" (FS2) reduces the underestimation of the carbon content over the entire profiles for T_D (Figs. 4, 5). For the oldest bare fallow, a better agreement between the data and these models is always obtained where SOM decomposition follows a first order kinetics (FS1). The reduction of the MSD value is due to a better representation of the standard deviation and the mean bias. For the steppe (control) plot, where the FOM amount is higher than in the bare fallow soils, and input from root exudates and mortality through the soil profile continuously adds FOM as energy supply to decomposers, the FS2 formulation reduces the MSD values when diffusion or both diffusion and advection are represented in a model (T_A and T_{AD}). Indeed, for T_A and T_{AD} transport parameterizations, a "priming" formulation of SOM decomposition decreases drastically the SB and the NU values. Finally, we also observe for all profiles and all schemes that when advection is represented (T_A and T_{AD}), the C move

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too rapidly from the first layer to the one below explaining why the C stock is always underestimated in the first layer.

Over the entire dataset, the best fit with the data over all the formulations is obtained for model VI, i.e. with representation of diffusion and advection (T_{AD}) and with priming (FS2). In the same configuration, when SOM mineralization is described as a first order kinetics, the C decomposition in the top layers is largely overestimated (Figs. 4, 5). Therefore, the MSD values are generally drastically reduced when "priming" is incorporated in a model for all the profiles but the oldest bare fallow. Thus, a "priming" formulation reduces the mean bias (T_A, T_D and T_{AD} for the steppe, 20YBF and 26YBF) and may improve the NU (T_D and T_{AD} for the steppe) or the LC (T_A, T_D and T_{AD} for 20YBF and 26YBF), as compared to a formulation based on first order kinetics (FS1).

3.2 The transport formulation

Considering the entire dataset, for each SOM mineralization formulation, the best fit is not always obtained with the same transport formulation. Indeed, when SOM mineralization formulation followed a first order kinetics (FS1), the best fits are obtained with the diffusion only (T_D) except for the oldest bare fallow 58YBF. For this latter plot, advection as a model process improves the value of the SB indicator indicating a reduction of the standard bias. When using the FS2 "priming" representation, the best fits are obtained with the formalisms including advection (Fig. 3). In this case, all the error indicators are reduced in comparison to diffusion only and the standard deviation (NU) and the shape (LC) are better-represented compare to advection only. The diffusion and advection model reproduces slightly better the profiles in comparison to the advection only model.

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4 Discussion

4.1 The representation of SOM decomposition

Our goal is to better separate the role of vertical transport mechanisms such as diffusion/advection given different formulation of SOM decomposition using a simple conceptual model of SOC decomposition. For the data we use, we first show that the priming representation proposed by Wutlzer and Reichstein (2008) shows off as a necessary process to reproduce the vertical profile of soil C. This "priming" formulation is superior to the simple and classical first order kinetics one. For each transport formulation, a better performance of models with a "priming" formulation is obtained for 10 of the 15 cases studied here (5 datasets with 3 transport formalisms). For the entire set of cases, the "priming" formulation reduced the standard bias and better reproduced the shape of C profiles (reduction of the LC values). For the youngest LTBF, the priming formulation better performed for each transport formulation for all the C profiles. For the steppe, a "priming" formulation better performs when advection only or both advection and diffusion are represented. Though, the lowest MSD value over the six models is obtained for the model with first order kinetics and diffusion only for the oldest bare fallow (58YBF), inclusion of priming still gave good results if advection is included in the transport model. For the case where a "priming" formulation improves the model output, the largest improvement is observed for the deep layers (> 40 cm) when FOM amount was low (Fig. 6). It was particularly the case for the steppe. For young LTBF, all the profile representation is improved for the "priming" formulation. Indeed, when SOM decomposition is described by first order kinetics the model over estimates the SOM decomposition in deep soil layers. This result is in agreement with the study of Dörr and Munnich (1989). It suggests that the SOM decomposers activity is largely controlled by the availability of FOM at the Kursk site, and that using a single decomposition rate for all the soil layers parameterized on the top layers might lead to largely over estimate SOM decomposition at depth (and underestimate it near the surface). This conclusion is in agreement with the results of Fontaine et al. (2007) who observe

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an important increase of SOM mineralization at depth when FOM is added in an in vitro experiment. However, for the oldest bare fallow soil, modelled FOM stock in the model is close to zero, particularly in deep soil layers. Thus SOM mineralization, when controlled by FOM amount, is very slow leading to under estimate the SOM decomposition. In our study, we might under estimate the FOM amount in the deep layer of the oldest bare fallow as we do not represent microbial turnover nor the FOM input due to microbial death. The amount of FOM available through microbial turnover is however probably not important compared to other FOM inputs in a "classical soil" as suggested by Kucharik et al. (2001). Nevertheless, in a bare fallow soil FOM inputs from the recycling of microbial biomass could be relatively important for the SOM decomposers community as previously suggested (Guenet et al., 2011a). Consequently, in the models where microbial biomass and turnover is not explicitly represented, we suggest to use the minimum values of the decomposition rate calculated by both formulations as suggested by Wutlzer and Reichstein (2008).

4.2 Transport mechanisms in face of SOM decomposition formulations

We found in the results section that for the FS1 formulation, the worst fit to the data is always observed when only advection is represented, except for the oldest bare fallow. When the FS2 ("priming") formulation is used, the worst fit was always with diffusion except for the steppe. However, the model V (FS2 and T_D) presents crossing points between the dashed lines (Fig. 5) and it suggests that this model may not be realistic. The advection rates obtained after optimization in this study are ten times higher than those presented in Bruun et al. (2007) but ten times lower than those presented in Braakhekke et al. (2011). For the diffusion coefficient, the values obtained here after optimization are also higher than those of Bruun et al. (2007) (one or two range of order) but this diffusion coefficient is a function of the bulk density (Braakhekke et al., 2011). Thus, differences in the bulk density between the soil used here and the one used by Bruun et al. (2007) might explain the different diffusion coefficients. Baisden et al. (2002) obtained good agreement between data and model output with a model

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which only use advection as transport mechanism. The advection rates in our study are in agreement with those observed by Baisden et al. (2002). In our case, except for the oldest bare fallow, when SOM decomposition follows a first order kinetic, the fit with the data could be improved when only diffusion is taken into account.

When "priming" is included in any of the conceptual models, we observe that both diffusion and advection must be represented to better fit the data. However, the oldest is the SOM, the closest are the MSD values between T_A and T_{AD}. Following the parsimony principles, we may consider for the 26YBF and the 58YBF, the most important transport mechanisms is only advection. In long-term bare fallows older than 40 yr, most of the labile C has been mineralized (Barré et al., 2010). Consequently, the SOM in this soil is quite different from the youngest bare fallow plots and from the steppe. For example particulate organic matter, i.e. decomposing plant residues, which are labile components of SOM are depleted from a temperate bare fallow in a few decades (Vasilyeva et al. in preparation). It suggests that different pools of SOM could be transported through different mechanisms. The more labile may be transported mainly by diffusion whereas the more stabilized may be transported by advection. Diffusion is often used to account for transport of plant debris and particulate organic matter by soil fauna. To our knowledge, this is the first time that different transport mechanisms are identified for different pools of C. This assumption must be tested against other soil profiles from bare fallow experiments, but if confirmed it suggests that soil models using different pools of C and aiming to represent the C distribution within a profile must use different transport mechanisms for labile and stable pools.

4.3 Transport mechanisms depending on the SOM decomposition formulation

We observed that the transport mechanism inducing the best fit for all the data but the oldest bare fallow is not always the same for each decomposition formulation and might therefore depend on the formulation used to described SOM decomposition. Indeed, when SOM decomposition is described by a first order kinetic, the best fit can only be obtained when only diffusion is used. But a better fit is obtained with both advection and

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diffusion as transport mechanisms when SOM decomposition depends on the FOM stock. This suggests that the FOM input regime may determine the most important transport mechanism. Moreover, the structural importance of transport mechanisms in a model depends on how the SOM decomposition is formulated. As a consequence, the use of such models to understand and separate mechanisms not directly observable may be a highly complex task, whose results could depend on the underlying assumption in the formulation of the SOM decomposition. For example, a first order kinetic model such as the one used in this study assumed that the microbial community responsible for SOM decomposition is stable in terms of biomass but also in terms of structure and physiology during the period considered. Several observations showed that microbial community structure, biomass and physiology are controlled by environmental conditions such as soil moisture (e.g. Williams, 2007; Guenet et al., 2011b) or temperature (e.g. Pettersson and Bååth 2003; Wu et al., 2009). Moreover, Hirsch et al. (2009) showed that the microbial community structure differ between grassland and bare fallow soils. The absence of explicit representation of the microbial community or biomass might explain also why our models do not fit so well with the data when first order kinetics are used. The second formulation obtained generally better fits but is not able to reproduce all the profiles perfectly. This latter assumes that there is a constant nutrient limitation on the microbial activity, which is implicitly represented in the parameters of the model. Mikhailova et al. (2000) showed that the N profiles in the Kursk site also differ between LTBF and the control. Thus, an explicit representation of the N cycle in the profile might decrease the MSD values. Finally, the effects of temperature and soil moisture are not represented in the models because not enough climate data was available. The absence of such effects may explained at least partially why the models and in particular the most complex do not perfectly fit with the data after optimization.

To our knowledge, this is the first time that the importance of SOM decomposition formulation on the transport formulation is showed and it could have important consequences on the representation of C transport in the model. Indeed, developing models inclusive of more and more mechanisms should likely improve our capacities to

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reproduce large scales datasets and to improve our understanding of the C cycle in the soil. Nevertheless, one must keep in mind that these mechanisms will interact with each other within the model structure and the choice of a certain representation of different mechanisms will depend on how others mechanisms are represented in the model.

5 Conclusion

First, all the models presenting crossing point between the dashed lines must be considered as not realistic. It indicates that the variance of parameters estimated is quite important inducing some non-realistic values for the some of them. In our case, these models are III (T_{AD} and FS1) and V (T_D and FS2). Regarding at the MSD values for the entire dataset, we may conclude that the better model over the six models tested would be the VI using the "priming" decomposition scheme and representing both advection and diffusion mechanisms. Moreover, this model obtains the lowest MSD values for half of the profiles. Nevertheless, the answer may also depends on the objectives fixed for the study. Using the Hugh et al. (2003) evaluation methods, we evaluate different characteristics of the models such as their capacities to reproduce the mean C stock value over the profile, the standard deviation around this mean value and the shape of the profile. For example, if the objective is to represent very well the shape of the steppe profile, we must use the model II with FS1 and T_D. But if the objective is to evaluate the mean C stock of the steppe, we must use the model IV with FS2 and T_A.

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Table 1. Model parameters summary.

Model parameter	Meaning	Optimized parameter	Prior estimates	Values for formulation I	II	III	IV	V	VI
I	Input of FOM ($tC\,ha^{-1}\,yr^{-1}$)	NO		34					
μ	Exponential rate parameter of FOM input from root mortality	YES	1.00	1.886	1.233	1.233	1.289	1.410	1.345
k_{FOM}	Decomposition rate of FOM	NO		0.4					
r	Respiration rate of FOM	NO		0.4					
k_{SOM}	Decomposition rate of SOM	YES	$33.3e^{-3}$	$6.26e^{-3}$	$6.01e^{-3}$	$6.05e^{-3}$	$5.38e^{-3}$	$6.05e^{-3}$	$5.48e^{-3}$
e	Humification rate	YES	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A	Advection coefficient ($mm\,yr^{-1}$)	YES	0.5	0.581	N.A	0.803	0.297	N.A	1.038
D	Diffusion coefficient ($cm^2\,yr^{-1}$)	YES	5.0	N.A	15.89	5.00	N.A	14.43	3.01
c	Influence of the FOM carbon pool in the SOM mineralization (priming parameter)	YES	30	N.A	N.A	N.A	26.81	33.77	31.29

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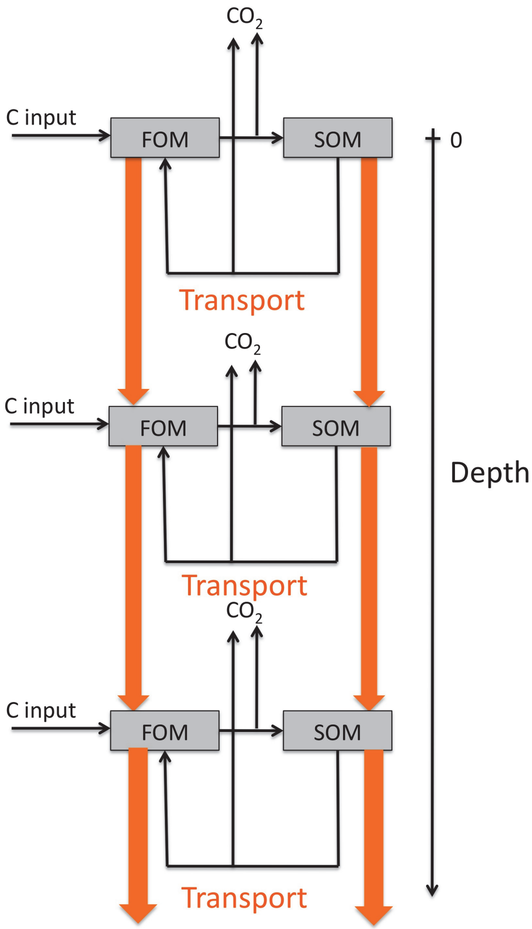

Fig. 1. Schematic representation of the fluxes and the pool in the model.

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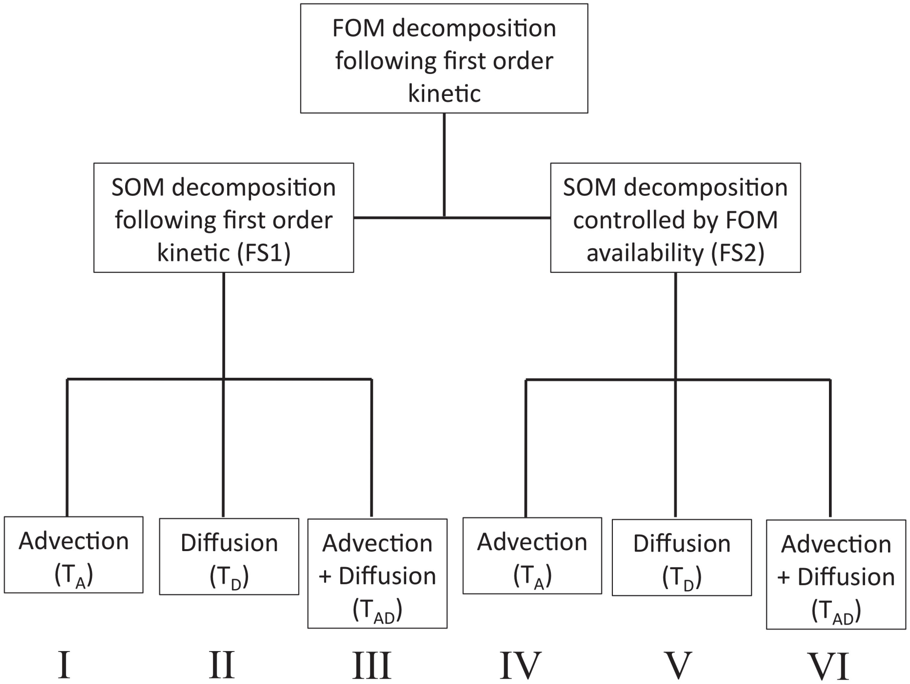

Fig. 2. Presentation of the six formulations used in this study.

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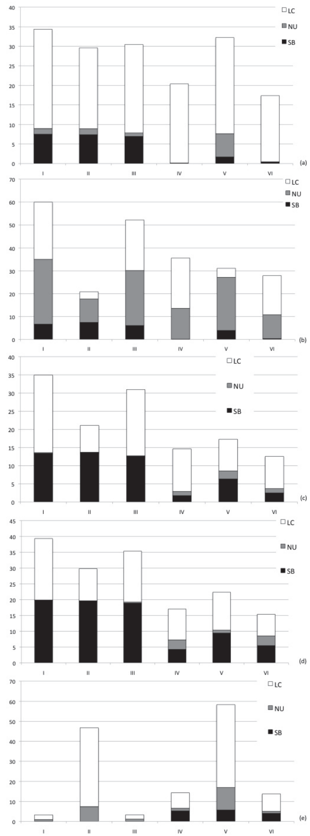

Fig. 3. Components of mean squared deviation (MSD) for the six formulations (roman number refer to those of the Fig. 2) for the entire dataset **(a)**, the steppe **(b)**, the 20 yr bare fallow **(c)**, the 26 yr bare fallow **(d)** and the 58 yr bare fallow **(e)**. The lowest the MSD value is, the best the fit is. The three components are lack of correlation (LC), non- unity slope (NU), and squared bias (SB).

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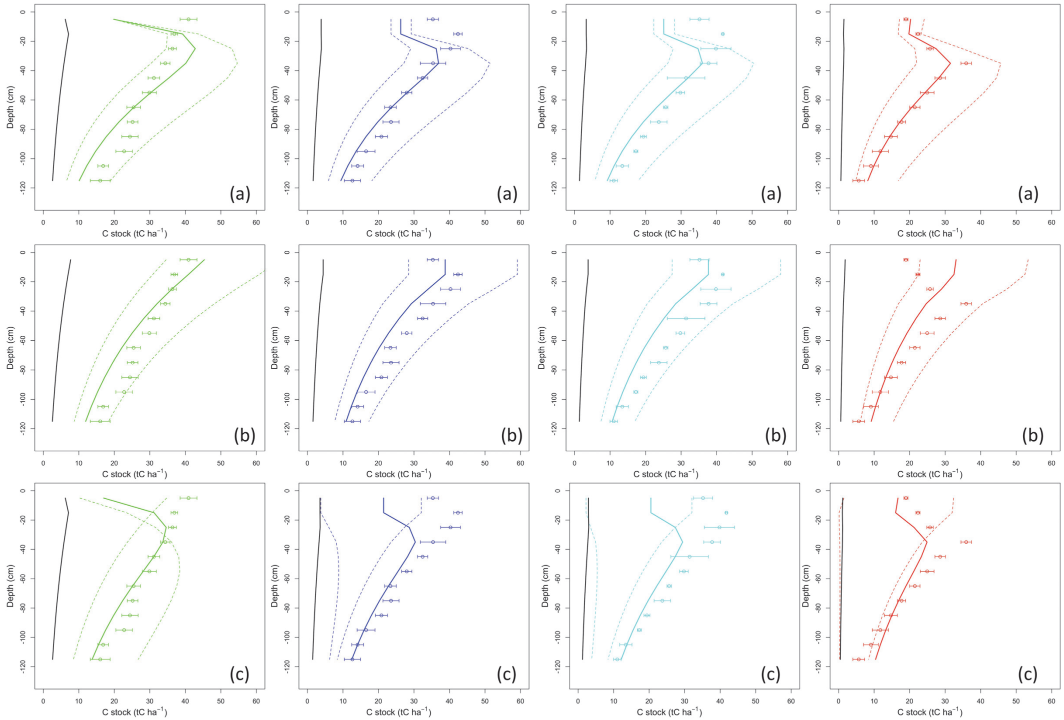

Fig. 4. Total Organic Carbon for the FS1 transport scheme (first order kinetics) and the three transport schemes (T_A **(a)**, T_D **(b)**, T_{AD} **(c)**). Measured C stocks are represented by the circles and modelled C stocks by the lines. Coloured continuous line represents the optimized model, whereas black line represents the model with the prior estimates. The dashed lines represent the model using the optimized parameters ± standard deviation. The steppe, the 20YBF, the 26YBF and the 58YBF are represented by the green lines, the dark blue lines, the light blue lines and the red lines respectively.

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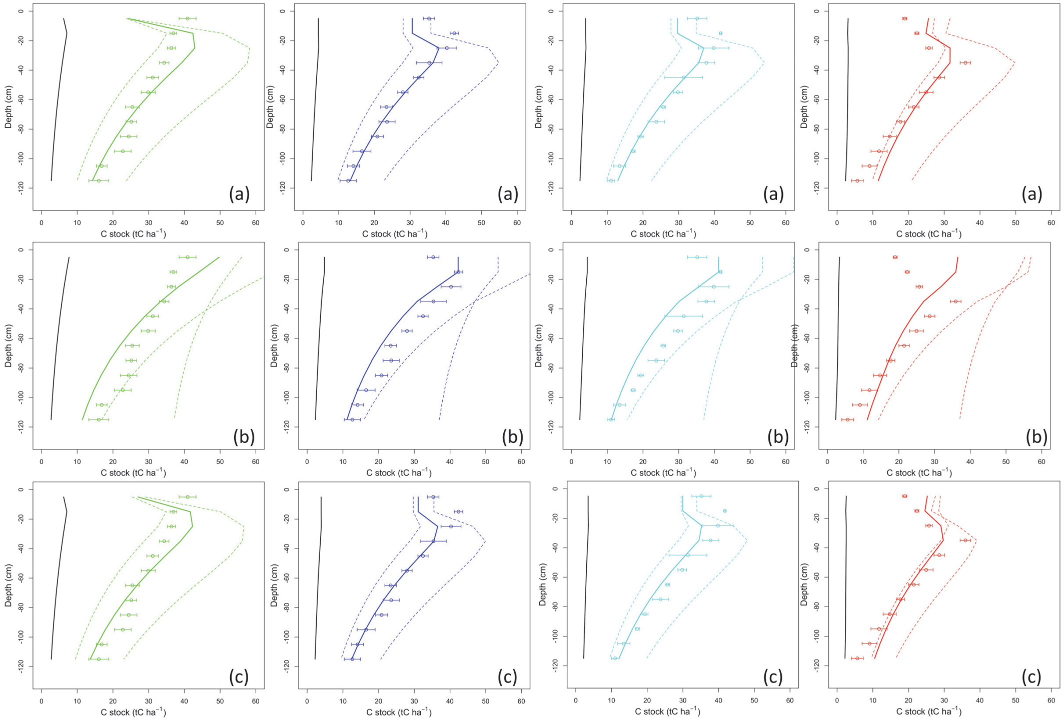

Fig. 5. Total Organic Carbon for the FS2 transport scheme (priming) and the three transport schemes (T_A **(a)**, T_D **(b)**, T_{AD} **(c)**). Measured C stocks are represented by the circles and modelled C stocks by the lines. Coloured continuous line represents the optimized model, whereas black line represents the model with the prior estimates. The dashed lines represent the model using the optimized parameters ± standard deviation. The steppe, the 20YBF, the 26YBF and the 58YBF are represented by the green lines, the dark blue lines, the light blue lines and the red lines respectively.

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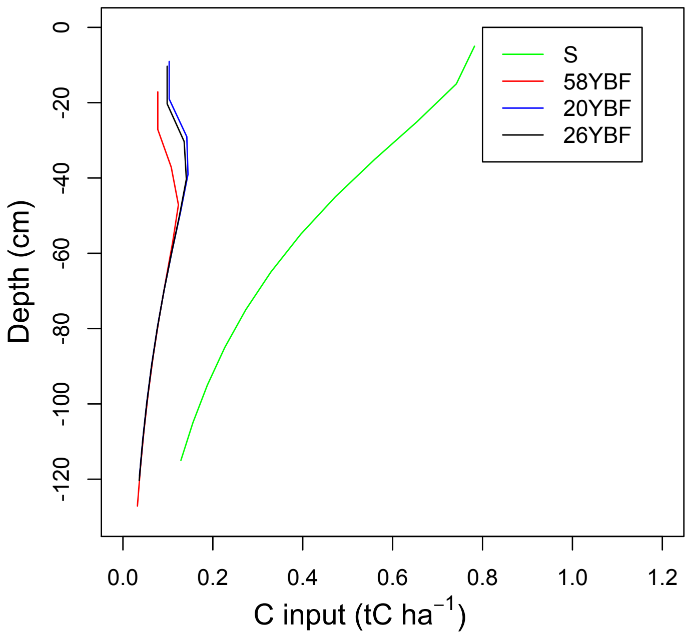

Fig. 6. Total Organic Carbon input for the four profiles calculated by the model. The steppe, the 20YBF, the 26YBF and the 58YBF are represented by the green lines, the dark blue lines, the light blue lines and the red lines respectively.

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