Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development
Discussions
Open Access

The use of radiocarbon ^{14}C to constrain carbon dynamics in the soil module of the land surface model ORCHIDEE (SVN r5165)

Marwa Tifafi[1], Marta Camino-Serrano[2,3], Christine Hatté[1], Hector Morras[4], Lucas Moretti[5], Sebastián Barbaro[5], Sophie Cornu[6], Bertrand Guenet[1]

[1]Laboratoire des Sciences du Climat et de l'Environnement, LSCE/IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France.
[2]CREAF, Cerdanyola del Vallès, 08193, Catalonia, Spain
[3]CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra 08193, Catalonia, Spain
[4]INTA-CIRN, Instituto de Suelos, 1712 Castelar, Buenos Aires, Argentina
[5] INTA-EEA Cerro Azul, 3313 Cerro Azul, Misiones, Argentina
[6]Aix Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

Corresponding authors: Marwa Tifafi (marwa.tifafi@lsce.ipsl.fr)

Abstract. Despite the importance of soil as a large component of the terrestrial ecosystems, the soil compartments are not well represented in the Land Surface Models (LSMs). Indeed, soils in current LSMs are generally represented based on a very simplified schema that can induce a misrepresentation of the deep dynamics of soil carbon. Here, we present a new version of the IPSL-Land Surface Model called ORCHIDEE-SOM, incorporating the ^{14}C dynamic in the soil. ORCHIDEE-SOM, first, simulates soil carbon dynamics for different layers, down to 2 m depth. Second, concentration of dissolved organic carbon (DOC) and its transport are modeled. Finally, soil organic carbon (SOC) decomposition is considered taking into account the priming effect.

After implementing the ^{14}C in the soil module of the model, we evaluated model outputs against observations of soil organic carbon and ^{14}C activity ($F^{14}C$) for different sites with different characteristics. The model managed to reproduce the soil organic carbon stocks and the $F^{14}C$ along the vertical profiles. However, an overestimation of the total carbon stock was noted, but was mostly marked on the surface. Then, thanks to the introduction of ^{14}C, it has been possible to highlight an underestimation of the age of carbon in the soil. Thereafter, two different tests on this new version have been established. The first was to increase carbon residence time of the passive pool and decrease the flux from the slow pool to the passive pool. The second was to establish an equation of diffusion, initially constant throughout the profile, making it vary exponentially as a function of depth. The first modifications did not improve the capacity of the model to reproduce observations whereas the second test showed a decrease of the soil carbon stock overestimation, especially at the surface and an improvement of the estimates of the carbon age. This assumes that we should focus more on vertical variation of soil parameters as a function of depth, mainly for diffusion, in order to upgrade the representation of global carbon cycle in LSMs, thereby helping to improve predictions of the future response of soil organic carbon to global warming.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

1 Introduction

The complexity of the mechanisms involved in controlling soil activity (Jastrow et al., 2007) and therefore the carbon flux from the soil to the atmosphere makes predicting the response of these systems to climate change extremely complex. Thus our ability to predict future changes in carbon stocks in soils using global climate models of the processes governing storage and destocking at variable time and space scales is currently heavily criticized (Todd-Brown et al., 2013; Wieder et al., 2013). Indeed, Earth System Models (ESMs) are increasingly used today in order to predict the future evolution of the climate. For instance, results of a set of ESMs are taken into account within the Intergovernmental Panel on Climate Change (IPCC) (Taylor et al., 2012) for assessment of the impacts of climate change and design of mitigation strategies. Hence, their predictions need to be as accurate as possible. These models represent the physical, chemical and biological processes within and between the atmosphere, ocean and terrestrial biosphere. They allow us to follow and understand, on the one hand the effect of the climate on carbon and vegetation and vice versa. However, ESMs are currently under development and some key processes in the global carbon cycle are still missing or not represented with the necessary details. One of the components of the ESMs is the land surface model (LSM). This component primarily manages the carbon cycle, energy and water on land and simulate the carbon uptake by plants between the atmosphere and the land, namely the gross primary production (GPP) and heterotrophic soil respiration.

Despite the importance of soils as a large component of the global carbon storage, the soil compartments are not well represented in LSMs (Todd-Brown et al., 2013). Indeed, carbon dynamics in soil described in LSMs are founded on the model “Century” (Parton et al., 1987) or the Roth-C model (Coleman et al., 1997) where soil carbon is represented as several pools, with different turnover rates for each pool. Carbon is decomposed in each pool, one part is then transferred from one pool to another and the other part is lost through heterotrophic respiration. In addition, soils are generally represented as a single-layer box in LSMs that do not take into account the evolution and variation of soil organic processes as a function of depth (Todd-Brown et al., 2013).

One way to reconcile thIS simplified representation of carbon dynamics of the models with the complexity of the data collected in the field is to integrate isotopic tracers into the models themselves and thus to facilitate the comparison between model outputs and data (He et al., 2016). Indeed, in order to be more pertinent in evaluating the parameters and the equations of the newly implemented processes, it is of interest implementing carbon isotope dynamics in the model itself, this to facilitate the comparison between model outputs and available observations, but also, thanks to an additive constraints on the model structure, to improve the model performances. For instance, radiocarbon is an important tool for studying the dynamics of soil organic matter (Trumbore, 2000). Indeed, ^{14}C acquired on soil organic matter, provide complementary information on the dynamics (temporal dimension) of soil organic matter. This tracer have the major advantage of being integrator of carbon dynamics on long time scales (a few decades to several centuries). It is therefore a very powerful tool to constrain conceptual schemes that may not be directly compared to variables measured in the field because of the conceptual description by pools non measurable (Elliott et al., 1996).

First, there is the natural radiocarbon produced at a constant rate in the upper atmosphere during the bombardment of cosmic rays. Thus it provides information on the dynamics of organic matter that has been stabilized by interaction with mineral surfaces and then been stored long enough for significant radioactive decay (Trumbore, 2000) since the half-life of ^{14}C is about 5730 years. Then, we distinguish the radiocarbon produced during the atmospheric tests of thermonuclear weapons in the early sixties which act as tracer thanks to the bomb peak of the 1960s (Delibrias et al., 1964; Hua et al., 2013). Atmospheric bomb testing in the late 1950's and early 1960's yielded for the abrupt increase of atmospheric ^{14}C concentration that doubles in 2-3 years. By exchange with ocean and terrestrial reservoirs, it decreases since but still remains above the natural background. As any other carbon isotopes, this ^{14}C was metabolized by the vegetation and transferred to soil. By measuring ^{14}C activity of soil sample and looking at the high values, it is possible to evaluate the amount of carbon introduced into the soil since the 1960s (Balesdent and Guillet, 1982; Scharpenseel and Schiffmann, 1977).

In this study, we present a new version of the IPSL-Land Surface Model called ORCHIDEE-SOM incorporating the ^{14}C dynamic in the soil. Thanks to this tracer, we evaluate the SOC dynamics, in particular by looking at the ^{14}C peak produced by atmospheric weapons testing and observed in the soils at four different sites having different biomes.

2 Materials and methods

2.1 ORCHIDEE-SOM overview

ORCHIDEE is the Land Surface Model of the IPSL (Institut Pierre Simon Laplace) Earth System Model (Krinner et al., 2005). It is composed of three different modules. First, SECHIBA (Ducoudré et al., 1993; de Rosnay and Polcher, 1998), the Surface-vegetation-atmosphere transfer scheme, describing the soil water budget and energy and water exchanges. The time step of this module is 30 min. Second, module of the vegetation dynamics which has been taken from the dynamic global vegetation model LPJ (Sitch et al., 2003). The time step of this module is 1 year. Finally, STOMATE (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems) module which essentially simulates the phenology and carbon dynamics with a time step of 1 day.

ORCHIDEE can be run coupled to a global circulation model. However, since our study focuses on changes in the land surface rather than on the interaction with climate, we run ORCHIDEE on off line configuration. In this case, the atmospheric conditions such as temperature, humidity and wind are read from meteorological dataset. The climate data CRUNCEP used for our study (6-hourly climate data over several years) were obtained from the combination of two existing datasets: the Climate Research Unit (CRU) (Mitchell et al., 2004) and the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996).

Our starting point is the ORCHIDEE-SOM version, based on the SVN r3340 version (Krinner et al., 2005), which is presented in details in Camino-Serrano et al. (2017). Figure 1 represents how the soil is described in this new version. Indeed, the major particularity of ORCHIDEE-SOM is that it simulates the dynamics of soil carbon for 11 layers from the surface to 2 m depth. First, litter is divided into four pools: metabolic or structural litter pools which can be found

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development Discussions
Open Access

below or aboveground. Only the belowground litter is modeled on 11 horizons, from surface to 2 m depth, however, the aboveground litter layer has a fixed thickness, 10 mm. Second, SOC is divided into three pools (active, passive and slow), following Parton et al. (1988), which differ in their turnover rates and which are discretized into 11 layers up to two meters. Then, dissolved organic carbon (DOC) is represented as two pools also discretized into 11 layers up to two meters: the labile DOC with a high decomposition rate and the recalcitrant DOC with a low decomposition rate (Camino-Serrano et al., 2017). Finally, another particularity of this version of ORCHIDEE-SOM is that the SOC decomposition is modified to account for the priming effect following Guenet et al. (2016).

Since the soil profile is divided into 11 layers, SOC and DOC transport following the diffusion is also described. SOC diffusion is actually a representation of bioturbation processes (animal (and plant) activity), whereas DOC diffuses through concentration gradients.

This is represented using the Fick's law (Braakhekke et al., 2011; Elzein and Balesdent, 1995; O'Brien and Stout, 1978; Wynn et al., 2005):

$$F_D = -D * \frac{\partial^2 C}{\partial z^2} \qquad (1)$$

Where F_D is the flux of carbon transported by diffusion in g C m^{-3} day^{-1}, D is the diffusion coefficient (m^2 day^{-1}) and C is the amount of carbon in the pool (DOC or SOC) subject to transport (g C m^{-3}). The diffusion coefficient is assumed to be constant across the soil profile in ORCHIDEE-SOM but the diffusion parameters (D) used in the equations for SOC and DOC are different.

2.2 ORCHIDEE-SOM-^{14}C

In ORCHIDEE-SOM, the different compartments (soil carbon input, litter, SOC, DOC and heterotrophic respiration) are presented as matrix with a single dimension referring to the total carbon. In order to introduce the ^{14}C, a new dimension has been added to all the variables cited above. Thus, all processes that apply to the total soil carbon are now also represented for ^{14}C. This new version including the ^{14}C will be called ORCHIDEE-SOM-^{14}C.

Several ways of reporting ^{14}C activity levels are available. We chose to use the *fraction modern*, with the F^{14}C symbol as advocated by Reimer et al. (2004) rather than absolute concentration of ^{14}C (that should be reported as Bq).

$$F^{14}\mathrm{C} = \left({A_S}/{0.95\, A_{OX1}}\right) * \left({0.975}/{0.981}\right)^2 * \left[\left(1 + {\delta^{13}C_{OX1}}/{1000}\right) / \left(1 + {\delta^{13}C_S}/{1000}\right)\right]^2 \qquad (2)$$

with A= $^{14}C/^{12}C$, S for sample, OX1 for Oxalic Acid 1, the ^{14}C international standard. F^{14}C is twice normalized: i- it takes into account isotopic fractionation by being normalized to a □^{13}C=-25‰ and ii- it corresponds to a deviation towards an international standard (i.e. 95% of OX1 as measured in 1950 – (Stuiver and Polach, 1977)). By propagating F^{14}C from atmosphere at the origin of vegetal photosynthesis to soil respired CO_2, there is no need to focus on ^{13}C isotopic fractionation all along the organic matter mineralization with F^{14}C.

To make easier the reading of the paper, we will further expressed F^{14}C as F^{14}C = A_{sample}/A_{ref} with normalizations included into A_{ref} and to simplify the notation with superscript and subscript F^{14}C will be restricted to F^{14}.

Since we focus on SOC dynamics, we did not include the ^{14}C in the plants but directly in the litter. The ^{14}C-litter is obtained by multiplying by F (atmospheric value) the total carbon's litter:

$$Litter\ (carbon14) = F^{14}_{atm} * \ Litter\ (carbon) \tag{3}$$

where F^{14}_{atm} is the $F^{14}C$ of atmosphere at the time of leaf growth (figure 2).

Thus, from the litter, all processes defined in section 2.1 that apply to total soil carbon are also represented for ^{14}C.

We also take into account the radioactive decay of ^{14}C. For that, we calculate the amount of ^{14}C as follow:

$$carbon14 = carbon14 - K_{decrease} * \ carbon14 \tag{4}$$

Where $k_{decrease}$ is the radioactive decay constant (=Ln2/5730) (Godwin, 1962)

Then, $F^{14}C$ of the soil is calculated back for carbon, per pool:

$$F^{14}_{Pool,z} = \frac{Carbon14_{Pool,z}}{Carbon_{Pool,z}} \tag{5}$$

with pool representing the active, slow or passive pool.

So finally, we calculate a mean $F^{14}C$ value per soil, according to the depth:

$$F^{14}_{Mean,z} = \frac{F^{14}_{active,z}*Carbon14_{active,z}+F^{14}_{slow,z}*Carbon14_{slow,z}+F^{14}_{passive,z}*Carbon14_{passive,z}}{Carbon14_{active,z}+Carbon14_{slow,z}+Carbon14_{passive,z}} \tag{6}$$

2.3 Sites description

2.3.1 French sites

Two Luvisol (WRB, 2006) (profiles located in the northern France were selected: Feucherolles and Mons sites. In Mons (49.87°N, 3.03°E), Luvisol, under grassland, are developed from several meters of loess and are thus well drained. The mean annual air temperature is 11°C and the annual precipitation is about 680 mm (Keyvanshokouhi et al., 2016). In Feucherolles, under oaks forest, site (48.9°N, 1.97°E), clay and gritstone deposits are found at approximately 1.5m depth. The mean annual air temperature is 11.2°C and the annual precipitation is about 660 mm (Keyvanshokouhi et al., 2016). Both soils are neutral to slightly acidic and are characterized by the presence of a clay accumulation Bt horizon with clay content reaching 30 % for Feucherolles and 27 % for Mons, while the upper horizons are poorer in clay (17 % for Feucherolles and 20% for Mons).

The ^{14}C data from the soils of both sites were obtained after chemical treatment done at LSCE using a protocol adapted to achieve carbonate leaching without any loss of organic carbon, and ^{14}C activity measurement performed by AMS at the French LMC14 facility (Cottereau et al., 2007).

2.3.2 Congo site

The studied site is located in Kissoko (4.35°S, 11.75°E). It belongs to the SOERE F-ORE-T field observation sites of Pointe Noire, Congo Republic. The mean annual air temperature is of about 25°C with low seasonal variations (± 5°C) and annual precipitation averages 1400mm with a dry season between June and September. The deep acidic sandy soil is a ferralic Arenosol

(WRB, 2006). The soil is characterized by a sand content larger than 90% (Laclau et al., 2000). Native vegetation is a savanna dominated by C4 plants (Epron et al., 2009) and the selected soil profile is under this native savanna vegetation. ^{14}C analyses were made in the same way as with the measurements for the two French sites, using the LSCE chemical treatment and the French LMC14 facility (Cottereau et al., 2007).

2.3.3 Argentina site

The Province of Misiones is located in northeastern Argentina. The climate is subtropical humid without a dry season, a 20°C of mean annual temperature and 1850mm of mean annual rainfall (Morrás et al., 2009). The profile used in this study is located in the southern part of Misiones (27°S, 55°W). Native vegetation is a forest dominated by C3 plants. The soil selected is an Acrisol (WRB, 2006). It's a red clay soil, strongly to very strongly acid with a clay content varying from 40% at the surface to 60% at 1m depth. ^{14}C measurements were made using a new Compact Radiocarbon System called *ECHo*MICADAS (Environment, Climate, Human, Mini Carbon Dating System) (Tisnérat-Laborde et al., 2015).

For the four sites, the SOC (kg m^{-3}), for each depth *z*, using the following equation was calculated using carbon content and bulk density data:

$$SOC_z = OCC_z * BD_z \quad (7)$$

Where *OCC* (wt %) is the carbon content and BD (kg m^{-3}) is the bulk density.

2.4 Different model tests

After the implementation of radiocarbon in the model, different tests were made (Table 2). Here we represent the outputs provided by three simulations:

i- Simulation using the initial version ORCHIDEE-SOM-^{14}C (Model_Control in figures and tables) in which no changes were made. The diffusion has been kept constant throughout the profile (D = 1.10^{-4} m^2 $year^{-1}$) and the other parameters are those of the detailed version in Camino-Serrano et al., (2017).

ii- Simulation using the initial version ORCHIDEE-SOM-^{14}C in which we modified some parameters following He et al. [2016] (Model_Test He in figures and tables). In brief, they used ^{14}C data from 157 globally distributed soil profiles sampled to 1-meter depth to evaluate CMIP5 models. Their results show that ESMs underestimated the mean age of soil carbon by a factor of more than six and overestimated the carbon sequestration potential of soils by a factor of nearly two. So, the suggestion (that we apply in this simulation) for the IPSL model was to multiply by 14 the turnover rate of the passive pool and by 0.07 the flux from slow pool to passive pool (Table 2). So, here, the diffusion was kept constant throughout the profile (D = 1.10^{-4} m^2 $year^{-1}$) but the turnover time of the passive pool increased from 462 years to 6468 years and the flux from the slow pool to the passive pool decreased from 0.07 to 0.049.

iii- Simulation using the initial version ORCHIDEE-SOM-^{14}C in which we assume that the diffusion, initially constant throughout the profile, varies as a function of the depth (Model_Test Diffusion in figures and tables) according to the equation below:

$$D(z) = 5.42.10^{-4} e^{(-0.04z)} \quad (8)$$

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development Discussions

Where D is the diffusion (m^2 $year^{-1}$) at a specific depth and z is the depth. This equation of diffusion varying as a function of depth following Jagercikova et al. (2014) and assume that bioturbation is higher in top soil than in deep soil.

2.5 Model simulations

First of all, in order to reach a steady state of the soil module, we ran the model over 12700 years (spinup). The state at the last time step of this spinup will then be used as initial state for the simulations. For this, the CRUNCEP meteorological data for the period 1901-1910 were used. This has been applied for Misiones, Feucherolles and Mons. However, for Kissoko, a first spinup similar to the other sites was carried out but a second one (over approximately 4200 years) was also done after the end of the first to take into account the change of the land cover from a tropical forest to a C4 savanna at this site (Schwartz et al., 1992). The atmospheric CO_2 concentration has been set at 296 ppm (year 1901, (Keeling and Whorf, 2006)) for the spinups. For each site, specific pH, clay content and bulk density values were used (Table 1). It should be noted that for these last data, only one value (the mean value on the profile) is provided as input for the model

The simulations were then run at a yearly time step, from 1900 to 2011. A yearly atmospheric CO_2 concentration value (Keeling and Whorf, 2006) is read for the sites. Of course, the same specific pH, clay content and bulk density values were used (Table 1).

Figure 2 shows the evolution of the $F^{14}C$ values in the atmosphere used in our model for Argentina, Congo and France (Figure 5 from Hua et al. (2013)). In fact, the values provided are classified into five zones, 3 in the Northern Hemisphere (NH) and 2 in the Southern Hemisphere (SH), corresponding to different levels of ^{14}C. For France, the values correspond to the NH zone 2, for the Congo to the SH zone 3 and finally for Argentina to the SH zone 1-2. Thus, for our simulations, a yearly value is read for each site.

An $F^{14}C$ value of 1.8 represents a doubling of the amount of ^{14}C in atmospheric CO_2. On figure 2, it can be noted that the values recorded in France (northern hemisphere) are higher than those in the Congo and Argentina (southern hemisphere). This is due to the preponderance of atmospheric tests in the northern hemisphere and the time required to mix air across the equator.

2.6 Statistical analysis

Simulating carbon processes in soil requires comparison between the model outputs and the measurements to test the model accuracy and possibly implement further improvement. Statistical analysis based on the statistics of deviation were done to evaluate the model–measurement discrepancy according to Kobayashi and Salam (2000) (where a detailed description of the method is provided). Here, we only represent the different equations used. x refers to the model outputs and y to the measurements.

$$RMSD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (9)$$

RMSD is the Root Mean Squared Deviation, which represents the mean distance between simulation and measurement.

$$MSD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 = (\bar{x} - \bar{y})^2 + \frac{1}{n}\sum_{i=1}^{n}[(x_i - \bar{x}) - (y_i - \bar{y})]^2 \quad (10)$$

MSD, the Mean Squared Deviation, is the square of RMSD. The lower the value of MSD, the closer the simulation is to the measurement.

$$SB = (\bar{x} - \bar{y})^2 \quad (11)$$

Where $\bar{x}$ and $\bar{y}$ are the means of x_i (model outputs) and y_i (measurements) respectively.

SB is a part of the MSD (Eq.13) and represents the bias of the simulation from the measurement.

$$SD_s = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (12)$$

SD_s is the Standard Deviation of the simulation.

$$SD_m = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (13)$$

SD_m is the Standard Deviation of the measurements.

$$r = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x}) - (y_i - \bar{y})}{SD_m\, SD_s} \quad (14)$$

Where r is the correlation coefficient between the simulation and measurements.

$$SDSD = (SD_s - SD_m)^2 \quad (15)$$

SDSD here, is the difference in the magnitude of fluctuation between the simulation and measurements.

$$LCS = 2SD_s\, SD_m(1 - r) \quad (16)$$

LSC represents the lack of positive correlation weighted by the standard deviations.
Finally, with all the above terms combined, the MSD can be written as:

$$MSD = SB + SDSD + LCS \quad (17)$$

For the different simulations, the MSD and its components were calculated according to the total soil carbon and to the $F^{14}C$.

3 Model results and evaluation

3.1 Outputs from simulation using the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control)

3.1.1 Simulated total soil carbon

Results from the initial version of ORCHIDEE-SOM-^{14}C show that in all the studied sites, the model succeeds in reproducing the trend of the total carbon profiles, with more carbon at the surface which decreases then according to the depth (Figure 3). Moreover, total soil carbon stock simulated down to 2m depth is in accordance with data in the case of Misiones and Feucherolles where the major difference mainly lies on the surface. This results in correlation coefficients of 0.55 and 0.6 respectively (Table 3). For the sites of Kissoko and Mons, an over-estimation of the total soil carbon is marked to 50cm deep for Kissoko (then it decreases) and up to 120cm deep for Mons. Correlation coefficients are 0.4 and 0.75 for Kissoko and Mons respectively (Table 3).

Metrics presented in Figure 4, showed that this version (ORCHIDEE-SOM-^{14}C) represents relatively well the observation from Feucherolles (MSD =206 kg C m^{-3}), whereas the other are highly overestimated (Kissoko, MSD = 1343 kg C m^{-3}; Misiones MSD=2180 kg C m^{-3}; Mons MSD=3355 kg C m^{-3}). Then, by detailing the different components of the MSD (Figure 4), we note that for Mons and Kissoko, standard bias (SB) is the major component of the MSD with 70% and 60% respectively. This reflects that the average of total soil carbon over the soil profile simulated by the model is primarily the origin of the deviation of the model outputs from data. The mean total soil carbon estimated by the model (Table 3) is more than four times the mean total carbon measured for Mons (64 kg C m^{-3} against 15 kg C m^{-3} respectively) and it is more than eight times that measured for Kissoko (34 kg C m^{-3} against 4 kg C m^{-3} respectively). This significant gap recorded in the case of the Kissoko site, where the measured SOC is very low, is probably due to its very particular soil characteristics (acidic sandy soil). ORCHIDEE is a global model that is not parameterized for such specific soil conditions

However, the main components of MSD for Feucherolles and Misiones are both SB (46% and 56% for Feucherolles and Misiones, respectively) and also LCS (53 and 31% for Feucherolles and Misiones, respectively). This means that for these two sites, the deviation between model outputs and measurements is mainly due to a variation of carbon stock estimation throughout the profile. The mean total soil carbon estimated in these both cases (Table 3) is only 1.7 to 2 times higher than those measured (65 kg C m^{-3} estimated against 31 kg C m^{-3} measured for Misiones and 24 kg C m^{-3} estimated against 14 kg C m^{-3} measured for Feucherolles).

The vertical profile of the SOC stock simulated was thereby globally not very far from that of the data. The overestimation, especially at the top, suggests that the distribution of the litter following the root profile and / or the vertical transport of SOC by diffusion are not correctly described in the model

3.1.2 Simulated F^{14}C

Regarding the ^{14}C activity, bulk F^{14}C profiles show classical pattern with higher ^{14}C activity, on the top, slightly influenced by the peak bomb more enriched years. Subsequently profiles show decreasing ^{14}C activity with depth (Figure 5).

The estimated profiles (Model-Control) follow the same trend with a decrease from the surface to the depth. However, there is a significant difference between the estimated values and those measured throughout the profile. The statistical analyzes (Figure 6) provide MSD values: 0.02 for Mons and Misiones, 0.03 for Kissoko and 0.09 for Feucherolles. The major component of the MSD in the four sites is the LCS, with a proportion always greater than 50% and which is even 90% for Mons, 80% for Misiones and 70% for Congo, however, it is only 55% for Feucherolles. The high proportions of LCS suggest that the model fails to reproduce the shape of the profile. The lower values estimated by the models reflect a more modern carbon age than in reality. This can be explained, first, by the fact that the root profile puts too much fresh organic carbon in deep soil. Afterwards, in ORCHIDEE, root profile is assumed to follow an exponential without modulation due to environmental conditions.

Then, SB's contribution does not exceed 7% for Misiones, Kissoko and Mons but reaches about 40% for Feucherolles. This reflects that the mean value of the F^{14}C estimated by the model and that obtained after the measurements are not very different, except for Feucherolles site (Table 4). Indeed, the average value estimated for Misiones is 0.920, very close to that measured at 0.930, 0.995 for Kissoko against 0.985 measured and 0.860 for Mons against 0.815 measured. Yet, the difference is greater for the Feucherolles site, the estimated value being 0.915 while the measurement is 0.725. This difference might be caused by the low $F^{14}C$ value measured at 150cm (0.257), that the model is not able to capture. This suggests that modeled deep soil carbon is much younger than the observed total soil carbon, probably because ORCHIDEE-SOM simulates a relatively small proportion of passive pool in the lower soil horizons (Figure 7), while an increasing proportion of passive carbon with soil depth could be expected.

In brief, SOC stocks are generally overestimated and soil carbon age in deep soils (as shown by the $F^{14}C$) is underestimated, suggesting that the turnover rate of passive pool is subject to improvements in ORCHIDEE-SOM.

3.2 Outputs from simulation using the initial version of the model ORCHIDEE-SOM-^{14}C including He's suggestion (Model_Test He)

3.2.1 Simulated total soil carbon

Figure 3 shows profiles output after He's suggestion implemented into ORCHIDEE-SOM-^{14}C (green dotted curves). Resulting profiles follow the same trend than observations but in this case (Model_Test He), the overestimation is very high from the surface to the depth. This is further confirmed by the metrics analysis (Figure 4). MSD values markedly increased, resulting in an even higher variance. Obviously, the major component of MSD in all cases is the SB (varying from 80% to 87%) reflecting an even more marked overestimation of the mean total carbon estimates: 128 kg C m^{-3} against 31 kg C m^{-3} for Misiones, 53 kg C m^{-3} against 4 kg C m^{-3} for Kissoko, 24 kg C m^{-3} against 14 kg C m^{-3} for Feucherolles and 131 kg C m^{-3} against 15 kg C m^{-3} for Mons.

3.2.2 Simulated $F^{14}C$

Model_Test He outputs (Figure 5, green dotted curves) for $F^{14}C$ are once again even further away from observations and MSDs (Figure 6) are much higher, except for Feucherolles, which MSD value in this case is lower. The MSD components for Feucherolles site show that the LCS increases from 0.05 to 0.06 whereas it is the SB which decreased from 0.04 to 0.03, again reflecting a variation of the profile more than a difference from the means.

Improvement of the model-measurement fit for the $F^{14}C$ at 150 cm in Feucherolles confirms that the deep soil carbon simulated by the control version of ORCHIDEE-SOM-^{14}C was excessively young, since the longer residence time of the passive pool reported by He et al. (2016) resulted in a higher proportion of passive pool across the soil profile (Figure 7), thus improving deep soil carbon age. Nevertheless, this test only improves the simulation of deep soil carbon in Feucherolles. On the contrary, this increase in carbon residence time has even more deviated the outputs of the model for all the other cases (Figure 5 and 6).

Indeed, taking the priming effect into account in this new version of ORCHIDEE has contributed to a 50% of decrease in carbon storage over the historical period. He's correction was also aimed at reducing this storage and is then of the same order of magnitude as the priming effect. Thus, applying He's correction to this version of the model, which takes into account the priming effect, contributes to a double correction for the same target, which then generates this important difference between model outputs and measurements. Moreover, the work of He et al. (2016) is done under the standard parameterization of ORCHIDEE based on Century, while ORCHIDEE-SOM was re-parameterized after adding several different processes, the priming effect among them (Camino-Serrano et al., 2017), what makes it difficult to associate results from her and this study.

3.3 Outputs from simulation using the initial version of the model ORCHIDEE-SOM-^{14}C with diffusion varying according to the depth (Model_Test Diffusion)

3.3.1 Simulated total soil carbon

Fick's law of diffusion is classically used in models to represent bioturbation (Elzein and Balesdent, 1995; Guenet et al., 2013; Koven et al., 2013; O'Brien and Stout, 1978; Wynn et al., 2005). Using a fixed diffusion constant implicitly suggests that soil fauna activity is uniform over the entire soil profile. This is fact generally the case of several models of diffusion especially used at the level of an ecosystem (Bruun et al., 2007; Guimberteau et al., 2017; O'Brien and Stout, 1978). However soil faunal activity vary naturally with depth, in addition, the characteristics of a soil, i.e. its structure and pore distribution, may vary depending on the depth, so, the diffusion coefficient should be depth-dependent (Jagercikova et al., 2014).

With Model_Test Diffusion, the carbon profiles (orange dashed curves) was improved compared to the initial outputs (Model_Control). The overestimation at the surface decreases at the four sites (Figure 3). In particular, the Misiones outputs fit very well the observed profiles. This is confirmed with lower MSDs for the four sites for this version compared to Model_Control showing a much smaller deviation from the measurements (Figure 4).

Anyway, the total SOC stocks simulated according to this third simulation are closer to the measured values and describing the vertical transport of SOC through diffusion varying according to the depth improves significantly the model outputs.

3.3.2 Simulated F^{14}C

Regarding the F^{14}C outputs, the simulations using the initial version ORCHIDEE-SOM-^{14}C in which we assume that the diffusion varies as a function of the depth (Model_Test Diffusion) results in an improvement of the F^{14}C profiles (orange dashes curves) especially for the sites Misiones, Mons and Kissoko (Figure 5). Statistical analyzes prove it with significantly lower MSDs. In addition, the proportion of LCS is 98%, 92% and 88% for Mons, Misiones and Kissoko, respectively, highlighting an estimated average very close to the measurements with a clear disparity, less marked than with the first two simulations, throughout the profile (Figure 6). Overall, the simulated F^{14}C to 2 m of depth according to this third simulation are in a better agreement with the measured values, thus, diffusion varying according to the depth improves significantly the model outputs.

Using a diffusion coefficient that varies as a function of the depth, seems to correct the overestimation of the surface total soil carbon by increasing the proportion of labile soil carbon pools in the first soil layers.

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development Discussions

When we look at the relative proportion of each of the soil carbon pools summing the total soil carbon at each soil layer (Figure 7), we note that it is mainly the distribution of the litter according to the depth which varied. In fact, the structural litter proportion is multiplied by about 2 in all four cases, and this proportion remains as large at the surface as at depth. This increase in litter proportion has also resulted in a decrease in the passive pool, more pronounced at the surface but also important at depth (except for Feucherolles where the decrease is only marked at the bottom). It suggests that the vertical carbon distribution, which is largely modified by the diffusion coefficient, greatly impacts the SOC and ^{14}C profiles, which is in line with Dwivedi et al. (2017) who found that the vertical carbon input profiles were important controls over the ^{14}C depth distribution.

In this study, the vertical transport of SOC and litter through diffusion has been improved by varying diffusion according to the depth. Further model development should explore the impact of the other process defining the soil carbon pools vertical distribution especially the distribution of the litter according to the root profile.

Overall, by using radiocarbon (^{14}C) measurements we have been able to diagnose internal model biases (underestimation of deep soil carbon age) and to propose further model improvements (depth-dependent diffusion). Therefore, the use of radiocarbon (^{14}C) tracers in global models emerges as a promising tool to constraint not only SOC turnover times in the long-term (He et al., 2016), but also internal SOC processes and fluxes that are has no direct comparison with field measurements.

4 conclusion

ORCHIDEE-SOM-^{14}C, is one of the first land surface models that incorporates the ^{14}C dynamic in the soil. Its starting point is ORCHIDEE-SOM, a recently developed soil model. We evaluated the new model ORCHIDEE-SOM-^{14}C for four sites in different biomes. The model almost managed to reproduce the soil organic carbon stocks and the ^{14}C content along the vertical profiles at the four sites. However, an overestimation of the total carbon stock throughout the profile was noted, but was mostly marked on the surface. Then, by using radiocarbon (^{14}C) measurements, we have been able to diagnose internal model biases (underestimation of deep soil carbon age) and to propose further model improvements (depth-dependent diffusion). The importance of diffusion has also been highlighted as by making it varies according to the depth, the model outputs have been improved. This suggests that, from now on, model improvements should mainly focus on a depth dependent parameterization, mainly for the diffusion. The next step will deal with the comparison of model outputs to data at larger scales to be able to run the new version ORCHIDEE-SOM-^{14}C at both regional and global scales.

Code availability

The version of the code is freely available here:

https://forge.ipsl.jussieu.fr/orchidee/wiki/GroupActivities/CodeAvalaibilityPublication/ORCHIDEE_gmd-2018-14C

Acknowledgement

This study, part of the MT's PhD, financed by the University of Versailles Saint Quentin, is within the scope of the ANR-14-CE01-0004 DeDyCAS project. Marta Camino-Serrano acknowledges funding from the European Research Council Synergy grant ERC- 2013-SyG-610028 IMBALANCE-P. Part of the data were acquired in the frame of the AGRIPED project (ANR 2010 BLAN 605).

References

Balesdent, J. and Guillet, B.: Les datations par le 14C des matières organiques des sols. Contribution à l'étude de l'humification et du renouvellement des substances humiqueétriques, Sci. du sol, 2, 93–111, 1982.

Braakhekke, M. C., Beer, C., Hoosbeek, M. R., Reichstein, M., Kruijt, B., Schrumpf, M. and Kabat, P.: Somprof: A vertically explicit soil organic matter model, Ecol. Modell., 222(10), 1712–1730, doi:10.1016/j.ecolmodel.2011.02.015, 2011.

Bruun, S., Christensen, B. T., Thomsen, I. K., Jensen, E. S. and Jensen, L. S.: Modeling vertical movement of organic matter in a soil incubated for 41 years with 14C labeled straw, Soil Biol. Biochem., 39(1), 368–371, doi:10.1016/j.soilbio.2006.07.003, 2007.

Camino-Serrano, M., Guenet, B., Luyssaert, S., Ciais, P., Bastrikov, V., De Vos, B., Gielen, B., Gleixner, G., Jornet-Puig, A., Kaiser, K., Kothawala, D., Lauerwald, R., Peñuelas, J., Schrumpf, M., Vicca, S., Vuichard, N., Walmsley, D. and Janssens, I. A.: ORCHIDEE-SOM: Modeling soil organic carbon (SOC) and dissolved organic carbon (DOC) dynamics along vertical soil profiles in Europe, Geosci. Model Dev. Discuss., 1–38, doi:10.5194/gmd-2017-255, 2017.

Coleman, K., Jenkinson, D. S., Crocker, G. J., Grace, P. R., Klír, J., Körschens, M., Poulton, P. R. and Richter, D. D.: Simulating trends in soil organic carbon in long-term experiments using RothC-26.3, Geoderma, 81(1–2), 29–44, doi:10.1016/S0016-7061(97)00079-7, 1997.

Cottereau, E., Arnold, M., Moreau, C., Baqué, D., Bavay, D., Caffy, I., Comby, C., Dumoulin, J.-P., Hain, S., Perron, M., Salomon, J. and Setti, V.: Artemis, the New 14C AMS at LMC14 in Saclay, France, Radiocarbon, 49(2), 291–299, doi:10.2458/azu_js_rc.49.2928, 2007.

Delibrias, G., Guillier, M. T. and Labeyrie, J.: Saclay natural radiocarbon measurements i, Radiocarbon, 6, 233–250 [online] Available from: http://radiocarbon.library.arizona.edu/radiocarbon/GetFileServlet?file=file:///data1/pdf/Radiocarbon/Volume6/Number1/azu_radiocarbon_v6_233_250_v.pdf&type=application/pdf, 1964.

Ducoudré, N. I., Laval, K. and Perrier, A.: SECHIBA, a New Set of Parameterizations of the Hydrologic Exchanges at the Land-Atmosphere Interface within the LMD Atmospheric General Circulation Model, J. Clim., 6, 248–273, doi:10.1175/1520-

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

0442(1993)006<0248:SANSOP>2.0.CO;2, 1993.

Dwivedi, D., Riley, W. J., Torn, M. S., Spycher, N., Maggi, F. and Tang, J. Y.: Mineral properties, microbes, transport, and plant-input profiles control vertical distribution and age of soil carbon stocks, Soil Biol. Biochem., 107, 244–259, doi:10.1016/J.SOILBIO.2016.12.019, 2017.

Elliott, E. T., Paustian, K. and Frey, S. D.: Modeling the Measurable or Measuring the Modelable: A Hierarchical Approach to Isolating Meaningful Soil Organic Matter Fractionations, in Evaluation of Soil Organic Matter Models, pp. 161–179, Springer Berlin Heidelberg, Berlin, Heidelberg., 1996.

Elzein, A. and Balesdent, J.: Mechanistic simulation of vertical distribution of carbon concentrations and residence times in soils, Soil Sci. Soc. Am. J., 59(5), 1328–1335, doi:10.1017/CBO9781107415324.004, 1995.

Epron, D., Marsden, C., M'Bou, A. T., Saint-André, L., d'Annunzio, R. and Nouvellon, Y.: Soil carbon dynamics following afforestation of a tropical savannah with Eucalyptus in Congo, Plant Soil, 323(1), 309–322, doi:10.1007/s11104-009-9939-7, 2009.

Godwin, H.: Half-life of radiocarbon, Nature, 195(4845), 984, doi:10.1038/195984a0, 1962.

Guenet, B., Eglin, T., Vasilyeva, N., Peylin, P., Ciais, P. and Chenu, C.: The relative importance of decomposition and transport mechanisms in accounting for soil organic carbon profiles, Biogeosciences, 10(4), 2379–2392, doi:10.5194/bg-10-2379-2013, 2013.

Guenet, B., Moyano, F. E., Peylin, P., Ciais, P. and Janssens, I. A.: Towards a representation of priming on soil carbon decomposition in the global land biosphere model ORCHIDEE (version 1.9.5.2), Geosci. Model Dev, 9, 841–855, doi:10.5194/gmd-9-841-2016, 2016.

Guimberteau, M., Zhu, D., Maignan, F., Huang, Y., Yue, C., Dantec-Nédélec, S., Ottlé, C., Jornet-Puig, A., Bastos, A., Laurent, P., Goll, D., Bowring, S., Chang, J., Guenet, B., Tifafi, M., Peng, S., Krinner, G., Ducharne, A., Wang, F., Wang, T., Wang, X., Wang, Y., Yin, Z., Lauerwald, R., Joetzjer, E., Qiu, C., Kim, H. and Ciais, P.: ORCHIDEE-MICT (revision 4126), a land surface model for the high-latitudes: model description and validation, Geosci. Model Dev. Discuss., 1–65, doi:10.5194/gmd-2017-122, 2017.

He, Y., Trumbore, S. E., Torn, M. S., Harden, J. W., Vaughn, L. J. S., Allison, S. D. and Randerson, J. T.: Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century, Science (80-.)., 353(6306) [online] Available from: http://science.sciencemag.org/content/353/6306/1419.full (Accessed 10 October 2017), 2016.

Hua, Q., Barbetti, M. and Rakowski, A. Z.: Atmospheric Radiocarbon for the Period 1950–2010, Radiocarbon, 55(4), 2059–2072, doi:10.2458/azu_js_rc.v55i2.16177, 2013.

Jagercikova, M., Evrard, O., Balesdent, J., Lefèvre, I. and Cornu, S.: Modeling the migration of fallout radionuclides to quantify the contemporary transfer of fine particles in Luvisol profiles under different land uses and farming practices, Soil Tillage Res., 140, 82–97, doi:10.1016/J.STILL.2014.02.013, 2014.

Jastrow, J. D., Amonette, J. E. and Bailey, V. L.: Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration, Clim. Change, 80, 5–23, doi:10.1007/s10584-006-9178-3, 2007.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., Joseph, D., Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha,

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development Discussions
Open Access

S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, Bull. Am. Meteorol. Soc., 77(3), 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Keeling, C. D. and Whorf, T. P.: Atmospheric CO2 records from sites in the SIO air sampling network., in Oak Ridge National Laboratory U.S. Departement of Energy, Oak Ridge, Tenn U.S., 2006.

Keyvanshokouhi, S., Cornu, S., Samouëlian, A. and Finke, P.: Evaluating SoilGen2 as a tool for projecting soil evolution induced by global change, Sci. Total Environ., 571, 110–123, doi:10.1016/j.scitotenv.2016.07.119, 2016.

Kobayashi, K. and Salam, M. U.: Comparing simulated and measured values using mean squared deviation and its components, Agron. J., 92(2), 345–352, doi:10.2134/agronj2000.922345x, 2000.

Koven, C. D., Riley, W. J., Subin, Z. M., Tang, J. Y., Torn, M. S., Collins, W. D., Bonan, G. B., Lawrence, D. M. and Swenson, S. C.: The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4, Biogeosciences, 10(11), 7109–7131, doi:10.5194/bg-10-7109-2013, 2013.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S. and Prentice, I. C.: A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19(1), doi:10.1029/2003GB002199, 2005.

Laclau, J. P., Bouillet, J. P. and Ranger, J.: Dynamics of biomass and nutrient accumulation in a clonal plantation of Eucalyptus in Congo, For. Ecol. Manage., 128(3), 181–196, doi:10.1016/S0378-1127(99)00146-2, 2000.

Mitchell, T. D., Carter, T. R., Jones, P. D., Hulme, M. and New, M. A.: A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901-2000) and 16 scenarios (2001-2100), Tyndall Cent. Clim. Chang. Res., 1–30 [online] Available from: http://www.ipcc-data.org/docs/tyndall_working_papers_wp55.pdf, 2004.

Morrás, H., Moretti, L., Píccolo, G. and Zech, W.: Genesis of subtropical soils with stony horizons in NE Argentina: Autochthony and polygenesis, Quat. Int., 196(1), 137–159, doi:10.1016/j.quaint.2008.07.001, 2009.

O'Brien, B. J. and Stout, J. D.: Movement and turnover of soil organic matter as indicated by carbon isotope measurements, Soil Biol. Biochem., 10(4), 309–317, doi:10.1016/0038-0717(78)90028-7, 1978.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S.: Analysis of factors controlling soil organic matter levels in great plains grasslands, Soil Sci. Soc. Am. J., 51(5), 1173–1179, doi:10.2136/sssaj1987.03615995005100050015x, 1987.

Parton, W. J., Stewart, J. W. B. and Cole, C. V.: Dynamics of C, N, P and S in grassland soils: a model, Biogeochemistry, 5(1), 109–131, doi:10.1007/BF02180320, 1988.

Reimer, P. J., Brown, T. A. and Reimer, R. W.: Discussion: reporting and calibration of post-bomb 14C data., Radiocarbon, 46(1), 1299–1304, doi:10.2458/azu_js_rc.46.4183, 2004.

de Rosnay, P. and Polcher, J.: Modelling root water uptake in a complex land surface scheme coupled to a GCM, Hydrol. Earth Syst. Sci., 2(2/3), 239–255, doi:10.5194/hess-2-239-1998, 1998.

Scharpenseel, H. W. and Schiffmann, H.: Radiocarbon dating of soils, a review, Zeitschrift für Pflanzenernährung und Bodenkd., 140(2), 159–174, doi:10.1002/jpln.19771400205, 1977.

Schwartz, D., Mariotti, A., Trouve, C., Van Den Borg, K. and Guillet, B.: Etude des profils isotopiques 13C et 14C d'un sol ferrallitique sableux du littoral congolais : implications sur la dynamique de la matière organique et l'histoire de la végétation, Comptes Rendus l'Académie des Sci. 2 Mécanique..., 1992, 315, p. 1411-1417. ISSN 0249-6305, 315, 1411–1417 [online] Available from: http://www.documentation.ird.fr/hor/fdi:37558 (Accessed 18 December 2017), 1992.

Sitch, S., Smith, B., Prentice, I. C., Arneth, a., Bondeau, a., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S.: Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model , Glob. Chang. Biol., 9(2), 161–185, doi:10.1046/j.1365-2486.2003.00569.x, 2003.

Stuiver, M. and Polach, H. A.: Reporting of 14C data, Radiocarbon, 19(3), 355–363, doi:10.1016/j.forsciint.2010.11.013, 1977.

Taylor, K. E., Stouffer, R. J. and Meehl, G. A.: An overview of CMIP5 and the experiment design, Bull. Am. Meteorol. Soc., 93(4), 485–498, doi:10.1175/BAMS-D-11-00094.1, 2012.

Tisnérat-Laborde, N., Thil, F., Synal, H.-A., Hatté, C., Cersoy, S., Gauthier, C., Kaltnecker, E., Massault, M., Michelot, J.-L., Noret, A., Noury, C., Siani, G., Tombret, O., Vigne, J.-D., Wacker, L. and Zazzo, A.: A new compact AMS facility measuring 14C dedicated to Environment, Climate and Human Sciences, in 22nd International Radiocarbon Conference, Dakar, Senegal. November 2015. Oral presentation, pp. 16–20., 2015.

Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C., Schuur, E. A. G. and Allison, S. D.: Causes of variation in soil carbon simulations from CMIP5 Earth system models and comparison with observations, Biogeosciences, 10(3), 1717–1736, doi:10.5194/bg-10-1717-2013, 2013.

Trumbore, S.: Age of soil organic matter and soil respiration: Radiocarbon constraints on belowground C dynamics, Ecol. Appl., 10(2), 399–411, doi:10.1890/1051-0761(2000)010[0399:AOSOMA]2.0.CO;2, 2000.

Wieder, W. R., Bonan, G. B. and Allison, S. D.: Global soil carbon projections are improved by modelling microbial processes, Nat. Clim. Chang., 3(10), 909–912, doi:10.1038/nclimate1951, 2013.

WRB: World reference base for soil resources 2006: a framework for international classification, correlation and communication., 2006.

Wynn, J. G., Bird, M. I. and Wong, V. N. L.: Rayleigh distillation and the depth profile of 13C/12C ratios of soil organic carbon from soils of disparate texture in Iron Range National Park, Far North Queensland, Australia, Geochim. Cosmochim. Acta, 69(8), 1961–1973, doi:10.1016/j.gca.2004.09.003, 2005.

Geoscientific Model Development Discussions
Open Access
EGU

Table 1. General description of the studied sites. The mean bulk density, pH and clay fraction values over the profiles were used as input for each site. For Mons and Feucherolles sites, min and max values of pH and clay fraction are provided between brackets.

Site name	Feucherolles	Mons	Kissoko	Misiones
Sampling Date	April 2011	March 2011	May 2014	May 2015
Location	France	France	Congo	Argentina
Coordinates	48.90°N, 1.97°E	49.87°N, 3.03°E	4.35°S, 11.75°E	27.65°S, 55.42°W
Elevation (m)	120	88	100	NA
Mean Annual Rainfall (mm)	660	680	1400	1850
Mean Annual Temperate (°C)	11.2	11	25	20
Soil Type (WRB)	Luvisol	Luvisol	Arenosol	Acrisol
Land Use	Temperate broad-leaved summergreen forest	Grassland	Native savanna	Tropical broad-leaved evergreen forest
Mean Bulk Density ($g\ cm^{-3}$)	1.34	1.4	1.48	1.15
Mean pH	5.9 (5.12-8.55)	6.9 (6.70-7.56)	5.2	5.2
Mean Clay Fraction (%)	20 % (13-30 %)	23 % (19-27 %)	5 %	58 %

Table 2. The main differences between the three simulations

	Flux from slow pool to passive pool	Turnover time of the passive pool (year)	Diffusion ($m^2\ year^{-1}$)
Model_Control	0.07	462	$D(z) = 1.10^{-4}$
Model_Test He	0.049	6468	$D(z) = 1.10^{-4}$
Model_Test Diffusion	0.07	462	$D(z) = 5.42.10^{-4}e^{(-0.04z)}$

Table 3. The correlation coefficient (r) between model outputs and measurements and the mean values (provided by the model and the measurements) over the profile according to total soil carbon (kg C m^{-3}), for the four sites. The results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to (He et al., 2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are provided.

		r	**Mean total soil carbon (kg C m^{-3}) Model**	**Mean total soil carbon (kg C m^{-3}) Measurements**
Misiones	Model_Control	0.55	65	31±0.30
	Model_Test He	0.50	128	
	Model_Test Diffusion	0.60	57	
Kissoko	Model_Control	0.40	34	4±0.30
	Model_Test He	0.40	53	
	Model_Test Diffusion	0.50	31	
Feucherolles	Model_Control	0.60	24	14±0.08
	Model_Test He	0.60	42	
	Model_Test Diffusion	0.70	21	
Mons	Model_Control	0.75	64	15±0.10
	Model_Test He	0.70	131	
	Model_Test Diffusion	0.80	54	

Table 4. The correlation coefficient (r) between model outputs and measurements and the mean values (provided by the model and the measurements) over the profile according to F^{14}C, for the four sites. The results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to (He et al., 2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are provided.

		r	**Mean Model**	**Mean Measurements**
Misiones	Model_Control	0.55	0.920	0.930±0.009
	Model_Test He	0.50	0.560	
	Model_Test Diffusion	0.60	0.900	
Kissoko	Model_Control	0.40	0.995	0.985±0.004
	Model_Test He	0.30	0.620	
	Model_Test Diffusion	0.55	0.995	
Feucherolles	Model_Control	0.55	0.915	0.725±0.005
	Model_Test He	0.55	0.550	
	Model_Test Diffusion	0.60	0.890	
Mons	Model_Control	0.75	0.860	0.815±0.005
	Model_Test He	0.70	0.510	
	Model_Test Diffusion	0.80	0.835	

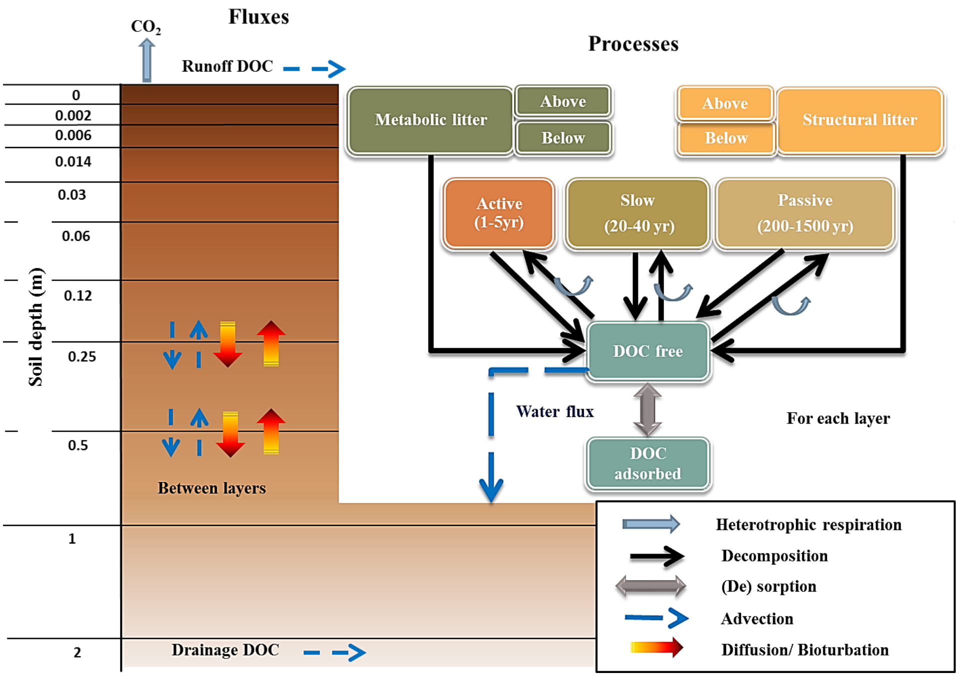

Figure 1. Overview of the different fluxes and processes in soil as presented in the version of ORCHIDEE-SOM adapted from Camino-Serrano et al. (2017)

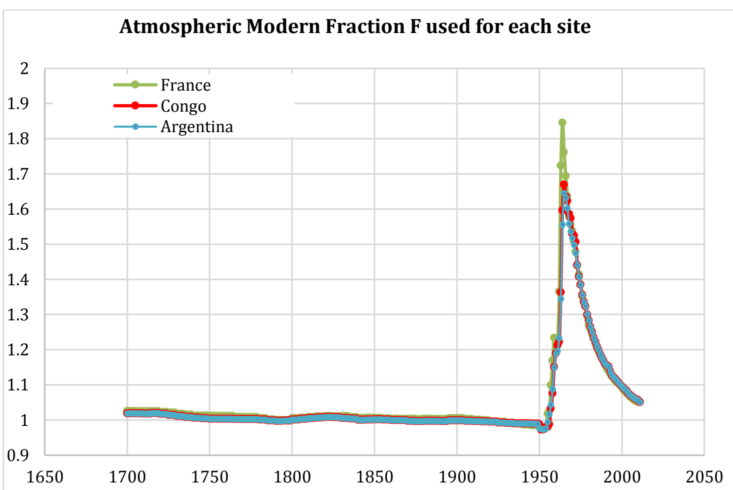

Figure 2. Evolution of the $F^{14}C$ of atmospheric CO_2 in Argentina, Congo and France (data from Hua et al. 2013)

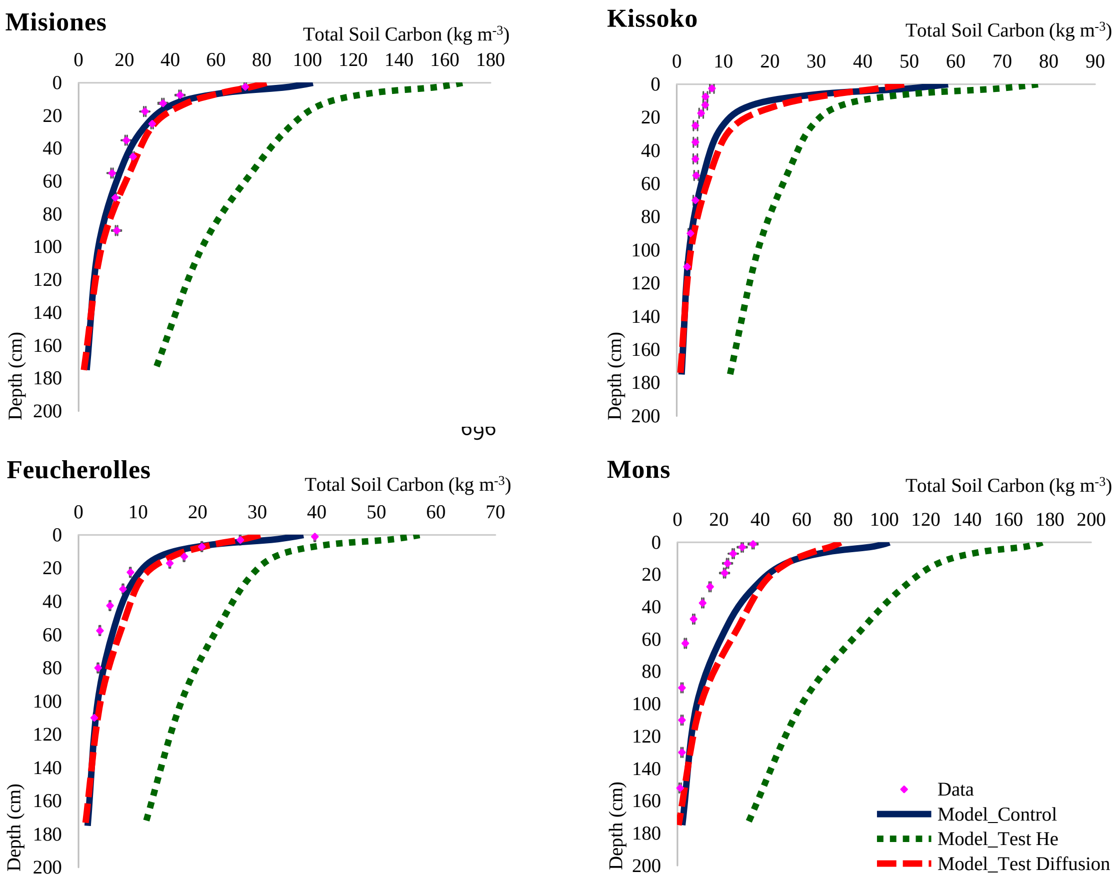

Figure 3. Total soil carbon (kg C m^{-3}) according to the depth, for the four sites. The results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to (He et al., 2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are shown

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development
Discussions
Open Access

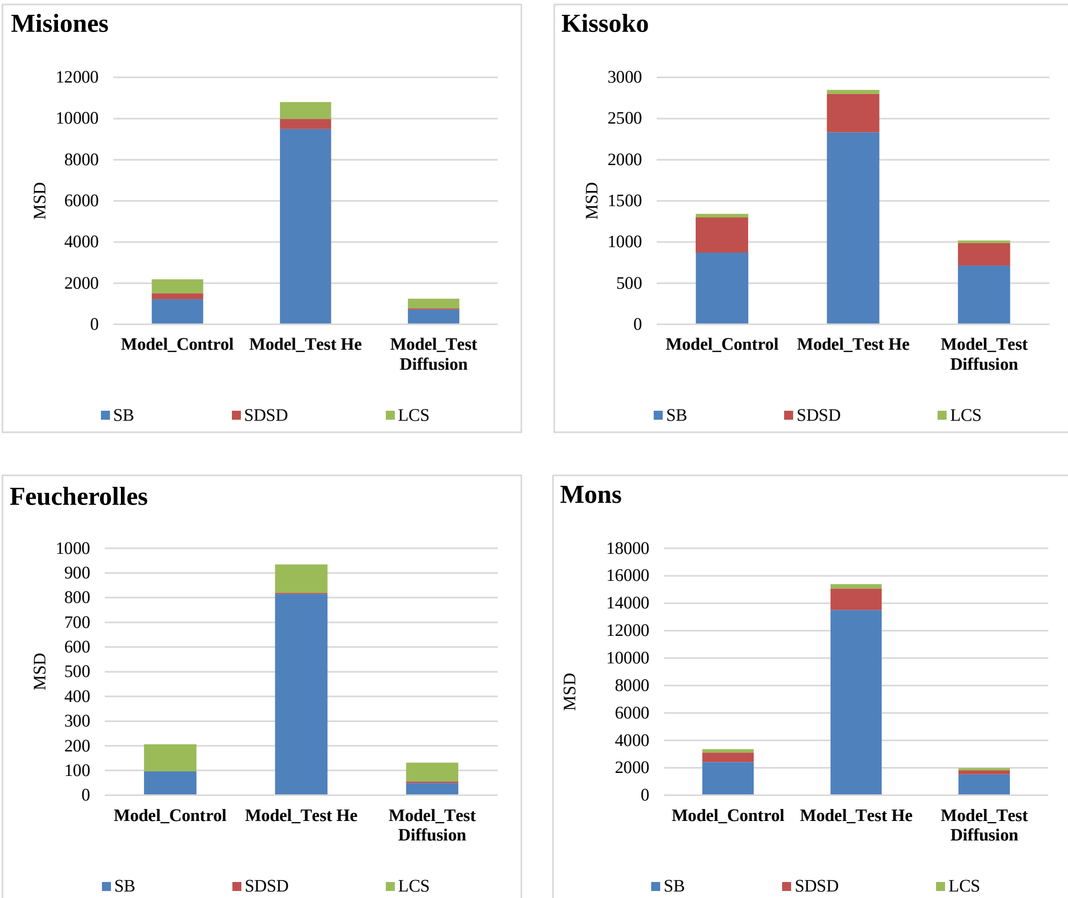

Figure 4. Mean Squared Deviation (MSD) and its components for total soil carbon (kg C m^{-3}): lack of correlation weighted by the standard deviation (LCS), squared difference between standard deviations (SDSD) and the squared bias (SB). For the four sites, the results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to (He et al., 2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are shown

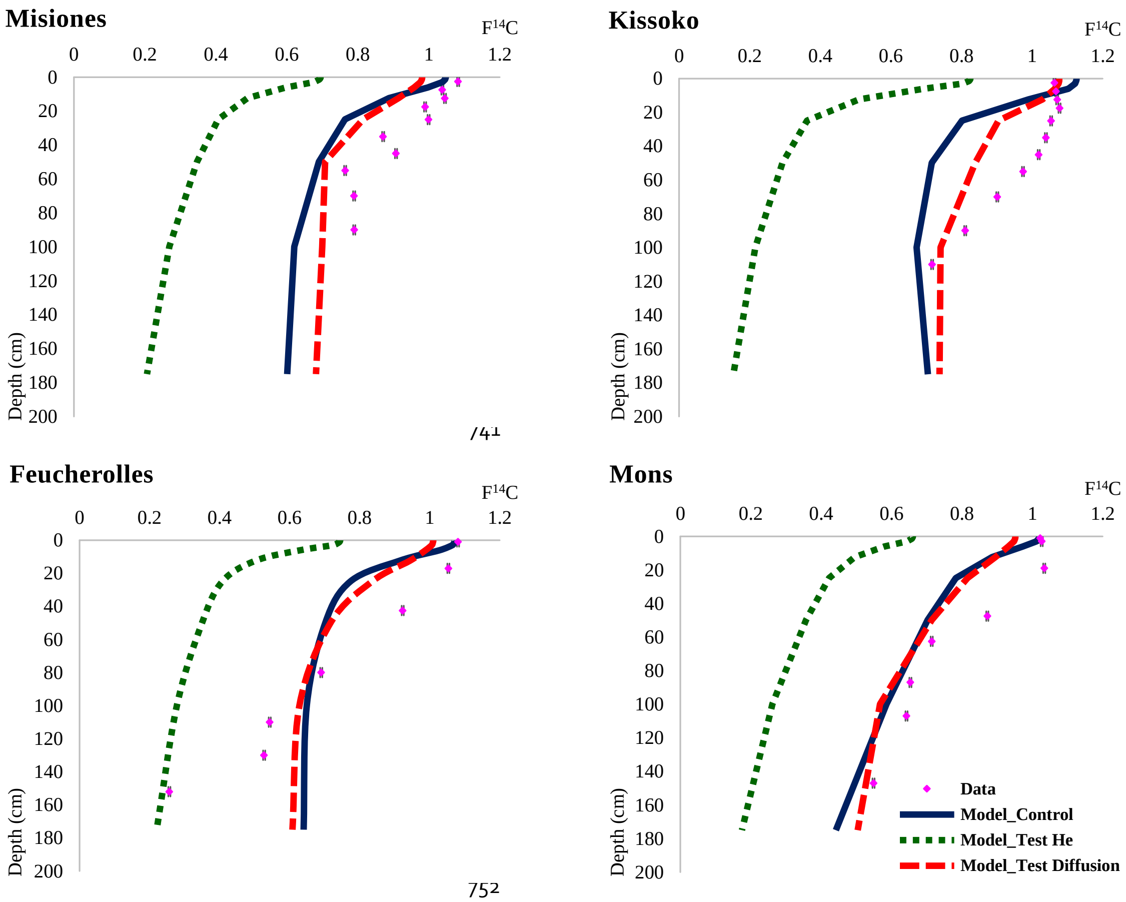

Figure 5. Modern fraction F^{14}C according to the depth, for the four sites. The results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to He et al., (2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are shown

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development
Open Access
Discussions

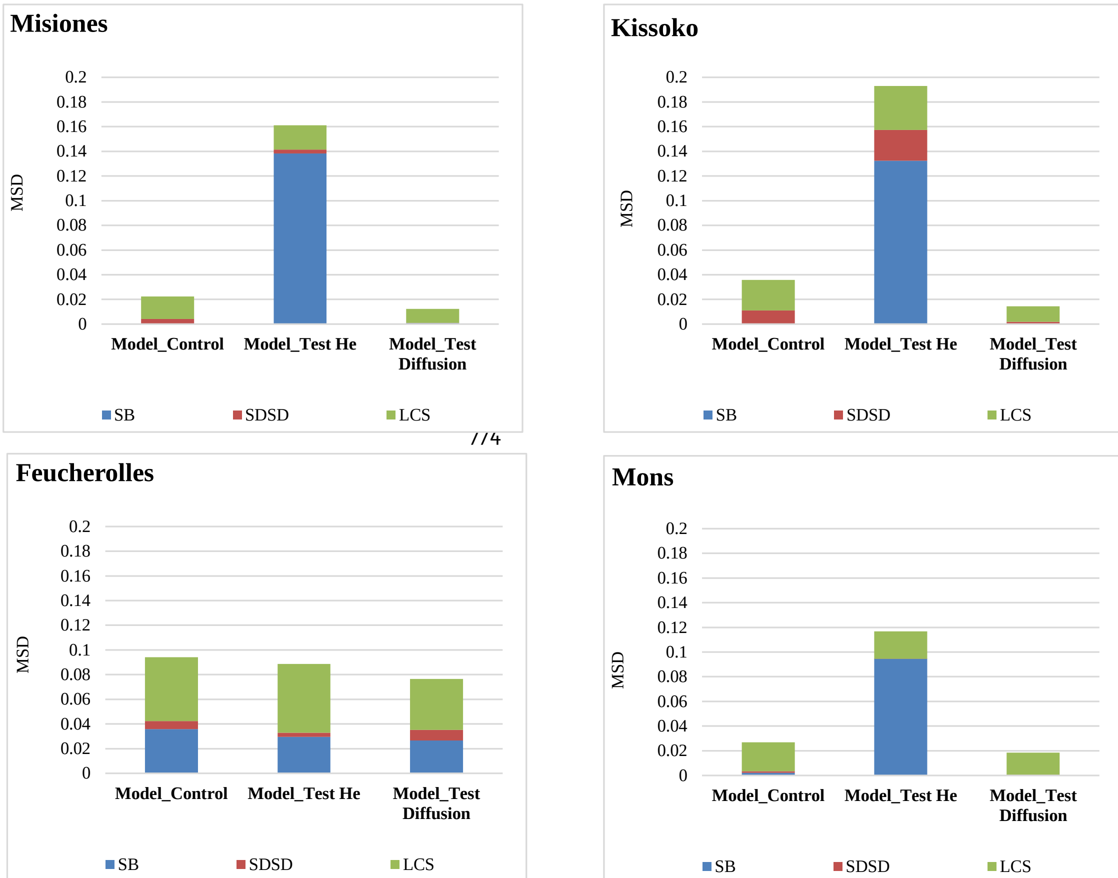

Figure 6. Mean Squared Deviation (MSD) and its components: lack of correlation weighted by the standard deviation (LCS), squared difference between standard deviations (SDSD) and the squared bias (SB). For the four sites, the results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to He et al., (2016) (Model_Test He) and diffusion varying according to the depth (Model_Test Diffusion), are shown

Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-102
Manuscript under review for journal Geosci. Model Dev.
Discussion started: 29 May 2018

Geoscientific Model Development Discussions
Open Access
EGU

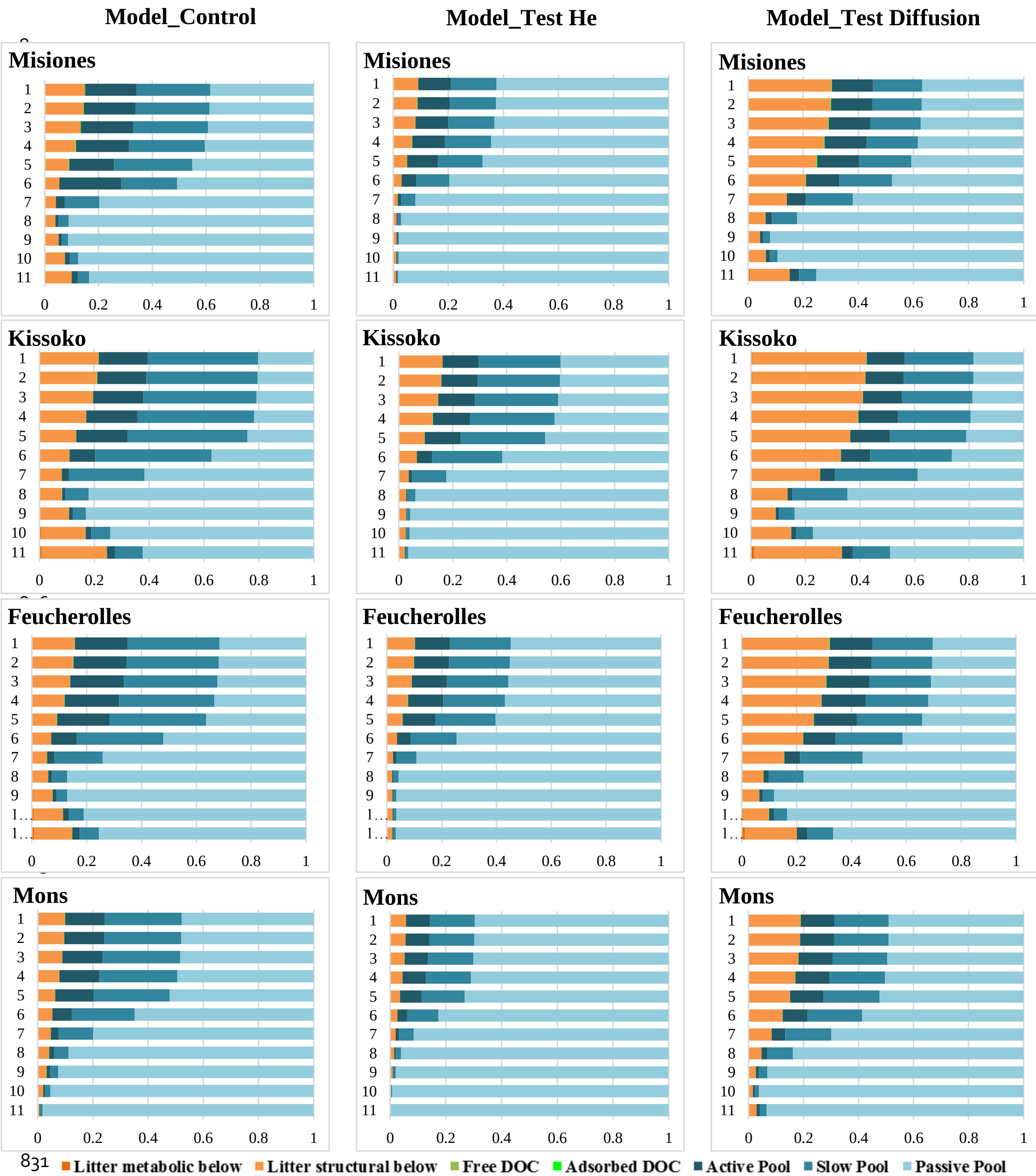

Figure 7. Relative proportion of each of the soil carbon pools summing the total soil carbon at each soil layer. The results of the initial version of the model ORCHIDEE-SOM-^{14}C (Model_Control, left pattern) as well as those from the version including the modification if the passive pool turnover rate and the slow-to-passive flux revised according to (He et al., 2016) (Model_Test He, pattern in the middle) and diffusion varying according to the depth (Model_Test Diffusion, right pattern), are shown