Effects of soil process formalisms and forcing factors on simulated organic carbon depth-distributions in soils.

Saba Keyvanshokouhi, Sophie S. Cornu, Francois Lafolie, Jérôme Balesdent, Bertrand Guenet, Nicolas Moitrier, Nathalie Moitrier, Cédric Nouguier, Peter Finke

To cite this version:

Saba Keyvanshokouhi, Sophie S. Cornu, Francois Lafolie, Jérôme Balesdent, Bertrand Guenet, et al.. Effects of soil process formalisms and forcing factors on simulated organic carbon depth-distributions in soils.. Science of the Total Environment, 2019, 652, pp.523-537. 10.1016/j.scitotenv.2018.10.236 . hal-01904523

Effects of soil process formalisms and forcing factors on simulated organic carbon depth-distributions in soils

Keyvanshokouhi, S.[a,b], Cornu, S.[a], Lafolie, F.[c], Balesdent, J.[a], Guenet, B.[d], Moitrier, N.[c], Moitrier, N.[c], Nougier, C.[c], Finke, P.[b]

a- Aix-Marseille Univ, CNRS, IRD, INRA, Coll de France, CEREGE, 13545 Aix en Provence, France
b- Ghent University, Department of Environment, Coupure Links 653, B-9000, Belgium
c- EMMAH, INRA, Université d'Avignon et des Pays de Vaucluse, 84000 Avignon, France
d- Laboratoire des Sciences du Climat et de l'Environnement (LSCE/IPSL), UMR8212 (CEA-CNRS-UVSQ), Université Paris-Saclay, 91198 Gif-sur-Yvette Cedex, France

Abstract

Soil organic carbon (OC) sequestration (i.e. the capture and long-term storage of atmospheric CO_2) is being considered as a possible solution to mitigate climate change, notably through land use change (conversion of cropped land into pasture) and conservation agricultural practices (reduced tillage). Subsoil horizons (from 30 cm to 1 meter) contribute to ca. half the total amount of soil OC, and the slow dynamics of deep OC as well as the relationships between the OC depth distribution and changes in land use and tillage practices still need to be modelled.

We developed a fully modular, mechanistic OC depth distribution model, named OC-VGEN. This model includes OC dynamics, plant development, transfer of water, gas and heat, mixing by bioturbation and tillage as processes and climate and land use as boundary conditions. OC-VGEN allowed us to test the impact of 1) different numerical representations of root depth distribution, decomposition coefficients and bioturbation; 2) evolution of forcing factors such as land use, agricultural practices and climate on OC depth distribution at the century scale.

We used the model to simulate decadal to century time scale experiments in Luvisols with different land uses (pasture and crop) and tillage practices (conventional and reduced) as well as projection scenarios of climate and land use at the horizon of 2100. We showed that, among the different tested formalisms/parametrizations: 1) the sensitivity of the simulated OC depth distribution to the tested numerical representations depended on the considered land use; 2) different numerical representations may accurately fit past soil OC evolution while leading to different OC stock predictions when tested for future forcing conditions (change of land use, tillage practice or climate).

Keywords

Climate change, pasture, reduced tillage, organic matter, OC projection, model formalisms

1. Introduction

Soil organic matter is the largest terrestrial carbon reservoir that is in constant exchange with the atmosphere and, consequently, a small change in this carbon reservoir can have a strong effect on atmospheric CO_2. Estimating the response of soil organic carbon (OC) to climate change is crucial (Smith et al., 2008; Minasny et al., 2017) because soil OC sequestration is being considered as a possible solution to mitigate climate change, converting atmospheric CO_2 into long-life soil organic carbon. Land use change (conversion of cropped land into pasture) and conservation agricultural practices (reduced tillage), considered as a strategy to sequester carbon in soil, have been extensively studied (Paustian et al., 1997; Jobbágy and Jackson, 2000; Post & Kwon, 2000; Lal, 2004). Nevertheless, the relationship between the OC depth distribution and changes in land use and tillage practices is still poorly understood (Jobbágy and Jackson, 2000; Lorenz and Lal, 2005) and controversial results have been reported concerning the effects of tillage reduction (Haddaway et al., 2016).

Thus, there is an urgent need to better predict the OC stock evolution under land use, management and climate change scenarios by the year 2100. Heretofore, most predictive modelling efforts (Smith et al., 2005; Xu et al., 2011; Lugato et al., 2014; Wiesmeier et al., 2016) concentrated on the upper 30 cm of soil, e.g. those based on RothC (Coleman et al., 1997) or Century (Parton, 1996). These models describe OC as an ensemble of organic pools with different decay dynamics, but do not consider other soil processes or depth distributions. However, while the upper 30 cm (topsoil - A Horizon) of soil profile represents the highest organic matter concentrations, recent studies show that subsoil horizons (from 30 cm to 1 meter) contribute to 30 to 63 % of the total amount of soil OC (Batjes, 2014). Consequently, OC stock prediction must not be restricted to the upper 30 cm of the soil but should also consider deep OC stocks. Indeed, Balesdent et al. (2018) indicated that "using multilayer soil modules in global carbon models could help to improve our understanding of soil–atmosphere carbon exchange".

However, deep OC dynamics is generally not considered in OC modelling approaches or only to a limited extent (Nakane, 1978; Elzein and Balesdent, 1995; Baisden et al., 2002; Guenet et al., 2013) because the transport mechanisms of OC into deep layers are not well understood. Indeed, their direct measurement of deep OC evolution is limited due to very low concentrations and very slow changes. Information on contribution of deep roots to OC stock is rarely available while obtaining data on deep OC decomposition is not possible without disturbing the processes involved. Therefore, these processes may be addressed either by using tracers as stable C isotopes (Balesdent et al., 2018) or by modelling approaches. Recent works emphasized the need for multilayer soil carbon modules (Campbell and Paustian, 2015; Luo et al., 2016). He et al. (2016) suggested that Ecological Soil Models “must better represent carbon stabilization processes and the turnover time of slow and passive reservoirs when simulating future atmospheric carbon dioxide dynamics";

The processes responsible for deep OC stock change are transport of dissolved OC, bioturbation, root input and decomposition. Several attempts were made to introduce these processes in OC dynamic modelling. (e.g., Hilinski, 2001; Braakhekke et al., 2011; Koven et al., 2013; Riley et al., 2014; Camino-Serrano et al., 2018). Nevertheless, for these key processes, several numerical representations (including the equations and parametrization) exist in the literature (e.g. Elzein and Balesdent, 1995; Jackson et al., 1996; Zeng, 2001; Koven et al., 2013 among others), and are often model-specific. The impact of these different numerical representations on the simulated OC depth-distribution should be evaluated. But because of model-specific formalisms, it is difficult to modify their parameterization because of their imbrication with the parameters of other processes.

In addition, at the century scale, when considering climate change 1) explicit transfer of water and heat should be considered and 2) inherent soil properties that are important for OC dynamic, as soil texture, bulk density and hydraulic properties, cannot be considered constant (e.g. Montagne et al., 2008; Boizard et al., 2013). As an example, soil OC content is related to the soil bulk density, which influences soil hydraulic properties and thus soil water content that in turn affect the OC decomposition. Because deep OC might be thousands years old and interacts dynamically with soil development, OC dynamics must be coupled with a model of pedogenesis. Therefore, the retroaction among soil properties much be taken into account explicitly.

Based in this analysis, we developed a fully modular OC depth distribution model, called OC-VGEN that provides a multilayer representation of the soil; takes into considerations among soils properties while modelling OC dynamics; allow considering landuse and tillage practices as well as most of the depth distribution processes considering their different formalisms.

The motivations for the development of OC-VGEN are not to add one model to the long list of existing soil C models (Campbell and Paustian, 2015), but to be able to test alternate formalisms for a given process. Hereto, we build OC-VGEN in a modular platform VSoil (Lafolie et al., 2014), that allows easy coupling of OC dynamics with other processes of soil development that interact with OC itself through feed-back loops, such as bioturbation or changes in soil chemistry, granulometry, porosity and hydraulic properties. Such model will allow users to identify where uncertainty about process formulations impacts the accuracy of relevant model outputs (such as OC depth distribution and its change over time), and thus, where more research is needed before OC-modelling can be successful and accurate.

OC-VGEN was then used to test the impact of 1) different numerical representations of root depth distribution, OC decomposition coefficients and vertical transfer by bioturbation; 2) forcing factors such as land use, agricultural practices and climate on OC depth distribution at the century scale. Therefore, the model was tested on long-term experiments on Luvisols that includes different land uses (pasture and crop) and tillage practices (conventional and reduced) and was forced by projection scenarios of climate and land use at the horizon of 2100.

2. Materials and Methods

2.1 Description of OC-VGEN model and its variations

OC-VGEN is a pedon scale, mechanistic model that takes into account factors of soil formation (climate, organisms, relief, parent material and human activities on soil) as initial or boundary conditions. It focuses on carbon dynamics and was developed in the VSoil modelling platform (Lafolie et al., 2014; Brimo et al., 2018). Other processes are fluxes of water, gas and heat, solid mixing processes such as bioturbation and tillage as well as plant development (Table 1 and Figure 1).

2.1.1 The VSoil platform

VSoil (Lafolie et al., 2014; Brimo et al., 2018) is a component-based platform that aims at designing, developing and implementing bio-geochemical and physical processes in soil. There is clear distinction in this platform between knowledge defined as *processes* and their mathematical representation defined as *modules*. Processes of any kind (physical, chemical, biological) influencing soil properties occurring within soil or at its boundaries (atmosphere and water table) can be described. Several numerical expressions and computer codes (modules) can be proposed to represent each of the processes. The modules associated to one process can differ by their numerical representations having different levels of complexity (from fully mechanistic to empirical), or by the numerical technique used to solve the equations or by the programming language (FORTRAN or C++). The processes and the associated modules can represent an actual process happening in the soil or an equation that leads to the evolution of soil properties. For example, the dynamic estimation of soil hydraulic properties and mass balance equations are defined as processes.

To build a model, a set of processes is selected, each process being associated to a module. The platform makes the connection between the processes/modules according to the defined input and outputs. Alternative versions of a same model can be designed by changing the modules associated to one or more processes of that model. In this paper we developed the OC-VGEN model in the VSoil platform as well as alternative versions of it by changing one module at a time as described below.

2.1.2. Simulation protocol

The impact of different numerical representations and parameters of plant rooting depth distribution, bioturbation and depth-dependent decomposition rate coefficient on the OC depth distribution was analyzed by running the model, changing one formalism (numerical representation or parameter) for each run. Table 2 summarizes the 6 formalisms: one reference run, three alternative formalisms for rooting depth (Alt1-RD_Jackson, Alt2-RD_Zeng, Alt3-RD_A/B, see also section 2.1.5), one alternative formalism for a depth-dependent decomposition coefficient (Alt4-OC_DDCoeff, see also section 2.1.3) and one alternative formalism for bioturbation (Alt5_Bioturb, see also section 2.1.6). These alternatives were performed for three different land use/agricultural practices known to affect OC in soil, namely cultivation with conventional tillage (M1) or reduced tillage (M2) and pasture (M3) for one site (Mons; Table 3, see also section 2.2.1). This made a total of 18 simulations (6 models run for 3 land use/practices - Table 2) representing the past until 2011 AD.

More specifically, for each simulation, a warming run (spin-up) was designed to simulate the initial state of the system. The spin-up runs consisted in a 300 years simulation except for the OC_DDCoeff version of the model for which the spin-up duration was extended to 1000 years. This was done because after 300 years, this model version still showed dependency of the initial situation. IOM was fixed as equal to the concentration of C horizon (105-125 cm). Then 1939-2011 scenarios were simulated for cultivation with conventional tillage, reduced tillage and pasture starting with the respective steady state obtained by the corresponding version of the model. Climatic condition for these runs are reported in Figure 2.

The impact of future climate change at horizon of 2100 was then analyzed based on 6 climatic scenarios (RCP2.6 and RCP8.5, each simulated by 3 climate models HadGEM, IPSL-CM5A and MIROC-ESM-CH, see Figure 3) for the three considered land use/tillage practices and the 6 considered model versions. This resulted in 108 additional simulations. These runs were designed as continuations of the previous one. Therefore, no spin-up steps were run for equilibration purposes.

The over-all layout of these simulations is shown in Figure 4.

2.1.3. Description of the OC-VGEN modules

2.1.3.1 The OC dynamic module

The OC dynamic module was developed based on the Rothc-26.3 model (Coleman et al., 1997) with some adaptation based on SoilGen (Finke and Hutson, 2008). In this model, fresh organic matter input is split between different pools (decomposable plant material (DPM), resistant plant material (RPM), biomass (BIO), humus (HUM), inert organic matter (IOM), Figure 1). Organic matter decomposes over time with half-life that differs strongly among pools (a month for DPM; one to three years for BIO, three to ten years for RPM, over 50 years for HUM, IOM is considered as stable in the model; Janik et al., 2002). Decomposition rates additionally depend on moisture deficit, temperature, soil cover and texture (Equation 1).

$$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z) r_z(z) \qquad (1)$$

Where $K(z)$ is the pool- and depth-dependent decomposition rate, $K_{0,p}$ is the pool dependent decomposition rate coefficient which is constant over depth and r, are the rate modifiers corresponding to T, the soil temperature calculated by the heat transfer module, SC, the soil cover, and Wt, both the moisture deficit and the < 2 µm fraction. The term $r_z(z)$

represents other depth dependent processes such as priming effect, i.e. the reduction of decomposition rates at depth as a result of low fresh substrate supply (Guenet et al., 2013; Shahzad et al., 2018). Koven et al. (2013) proposed an exponential function for $r_z(z)$, that decreases with depth to account for those processes (Equation 2).

$$r_z(z) = exp\frac{-z}{z_\tau} \quad (2)$$

where z_τ is the e-folding depth of the intrinsic decomposition rates. This depth was optimized by Koven et al. (2013) to 40 cm.

Temperature, moisture deficit and < 2 µm fraction are also depth dependent and are calculated using the same equations from the RothC26.3 model (Jenkinson and Coleman, 2008)

Soil moisture deficit corresponds to the difference between potential evapotranspiration and precipitation, being vertically distributed according to air filled porosity depth profile derived from the water transfer module.

At last, the partition coefficient among RPM/DPM pools in litter (the only pools represented in litter) is a function of the vegetation type/land use.

This module was implemented in VSoil platform as a core of OC-VGEN model to account for the dynamics of organic carbon in soil and used with $r_z(z)$ equals to one except for one simulation in which the impact of the decomposition coefficient formalism on OC depth distribution is evaluated (the scenarios are summarized in Table 2). While in the A horizon, the OC decomposition rate corresponds to that calibrated in SoilGen, it decreases exponentially below that horizon.

2.1.3.2. Water, heat and gas transfer modules

OC-VGEN uses Richard's equation to simulate the flow of water and advection-diffusion equations to model flow of heat and gas. A central-difference Crank-Nicholson approach is used to solve transport equations. It was developed after Pastis (Cannavo et al., 2006). Upper boundary conditions in water module allow for surface infiltration, evaporation and zero flux, while the lower boundary accounts only for free drainage in this study. When the soil infiltrability is exceeded, a water runoff module simply returns a soil surface potential to zero. Additionally, the soil cover fraction limits the evaporative flux at the upper boundary. This fraction is a function of the vegetation.

Soil hydraulic properties are simulated by the model once a year by the Hypress pedotransfer function based on the texture, OC and the bulk density (Wösten et al.,1999; adapted by Finke, 2012). Soil bulk density, water content and porosity are used to calculate soil heat capacity and thermal conductivity. Diffusive heat flux and transport by water are simulated.

2.1.3.3. Plant development modules

The plant development modules aim at bringing organic carbon into soil and up taking water from it. They consist in two modules: a plant development module and a module of water uptake by roots (Figure 1).

The plant development module provides organic matter input and root distribution profile. The organic matter input to soil consist in an input file indicating OC input through Net Primary Production (NPP) or/and organic amendments. This input is subsequently split between the above and below ground pools. Both pools then decay over time with similar equations as described in organic matter dynamic module. The ratio of above to below ground fresh organic input and the DPM/RPM ratio depend on the vegetation type/land use.

The plant root depth distribution is defined by a root density function and a rooting depth. The first consist in the formalism of root depth distribution while the latter is a parameter of that formalism.

Generally, in literature the root depth distribution formalism is represented by an exponential equation, with some variations among authors. OC-VGEN originally uses Equation 3 for permanent vegetation considering a steady rooting profile.

$$RDF(z) = \alpha . e^{-\alpha z} \tag{3}$$

where, RDF (m_{root} m^{-3}_{soil}) is the root density function calculated for each compartment inside the maximum rooting depth, z, represents the depth (m) and α is equal to 4 m^{-1} based on Finke (2012).

Davidson et al. (1978) proposed a root density function for crops in which the root is assumed to be growing within the year based on the pre-defined dates of planting, germination and root maturity according to Equation 4.

$$RDF(z,t) = R_{max}(t) exp(-\beta z^2) cos \frac{\pi z}{2L(t)} \tag{4}$$

in which, R_{max} is the maximum root density at z=0, z is the soil depth and L is the depth of the bottom of root zone, and β is an empirical function of the number of days since planting up till root maturity, originally developed for corn crops. At harvest, plant roots are no longer active regarding the uptake of water from the soil. For more details, see Davidson et al. (1978). This approach was used in OC-VGEN as used previously in the SoilGen model (Finke, 2012) for crops.

On the other hand, Jackson et al. (1996) fitted the function developed by Gale and Grigal (1987) to a global data set of root profile measurements and reached a global average rooting distribution function (Equation 5) that is common for the different plant groups (grass, shrubs, crop, trees).

$$RDF(z) = -ln(\beta) . \beta^z \tag{5}$$

where, β is the depth coefficient estimated by fitting to the measured data for each vegetation type. β is equal to 0.943 and 0.961 with r^2=0.88 and 0.82 for pasture and crop respectively.

Zeng (2001) fitted a double exponential equation (Equation 6) on the rooting depths reported by Canadell et al. (1996). This equation is an improved version of Jackson et al. (1996).

$$RDF(z) = \frac{1}{2}\left(a.e^{-az} + b.e^{-bz}\right) \tag{6}$$

with a equals 10.74 and 5.558 m^{-1}, and b, 2.608 and 2.614 m^{-1}, for pasture and crop respectively.

The parametrizations for rooting depths result in three different root depth distribution formalisms (Table 2). These formalisms include different choices for the distribution of fresh organic matter over the litter layer (aboveground) and rooted layers (belowground), which are expressed by above/below ground ratios (Table 2). . The two alternative formalisms (Jackson et al., 1996; Zeng, 2001) and the corresponding parametrizations were implemented in VSoil platform to create three alternative model versions (RD_Jackson, RD_Zeng and RD_A/B – summarized in Table 2). Note, that in all the above cases *RDF* is scaled to sum to 1 over the rooted zone.

Lastly, root water uptake calculation, a sink term in Richard's equation, is based on LEACHC (Hutson, 2003). This function optimizes the root water potential to minimize the difference between the transpiration demand and the flux of water from the soil to the roots taking into account the fraction of active roots present, the soil-water matrix potential (m) and hydraulic conductivity (m s^{-1}) at each soil layer. The transpiration demand is calculated from the potential evapotranspitation and the vegetation development provided by the crop development module.

2.1.3.4 Mass mixing modules

Mass mixing processes considered in OC-VGEN are bioturbation and tillage.

Bioturbation is classically described in the literature based on the diffusion equation (Elzein and Balesdent, 1995; Jarvis et al., 2010; Tonneijck et al., 2016).

$$\frac{\partial M_{OC}(z,t)}{\partial t} = D(z)\frac{\partial^2 M_{OC}(z,t)}{\partial z^2} \tag{7}$$

while $D(z)$ is the diffusion coefficient and M_{OC}, the organic carbon mass. $D(z)$ has been classically considered as constant through depth. Nevertheless, Jagercikova et al. (2014) recently introduced the depth-dependent diffusion coefficient that exponentially decreases in depth (Equation 8).

$$D(z) = D_0\, e^{-bz} \tag{8}$$

where D_0 is the diffusion coefficient at the surface ($m^2\ s^{-1}$) and b, the parameter of exponential decrease (m^{-1}).

Jagercikova et al. (2014), fitted Equation 8 to ^{137}Cs activities measured on the long-term experiment site considered in this study and obtained the following values of D_0 and b for the pasture profile: $D_0 = 5.42 \pm 1.81\ cm^2\ yr^{-1}$ and $b = 0.04 \pm 0.01\ cm^{-1}$. No ^{137}Cs was detected below 50 cm suggesting a negligible bioturbation below that depth.

A different modelling approach for bioturbation, was introduced in SoilGen2.24 model (Finke, 2012). In this approach a portion of each soil layer is distributed vertically among the other soil layers of the bioturbated depth and then homogenized with the remaining soil in each layer to predict the soil properties at each compartment after the process of vertical mixing. The mixing proportions per layer and the mixing depths are yearly model inputs.

Both formalisms include the redistribution of both soil solid and liquid phases. OC-VGEN originally uses the approach used in SoilGen2.24. In addition, the diffusive bioturbation is implemented in the VSoil platform as an alternative to allow for evaluation of the impact of bioturbation formalism on OC depth distribution (the alternative model created using this module is called Bioturb and is summarized in Table 2).

Tillage was implemented after SoilGen2.24 (Finke, 2012). In this model, as for bioturbation, a portion of each soil compartment is distributed vertically among the other soil layers of the tilled depth and then homogenized with the remaining soil in each layer to predict the soil properties at each layer after the process of vertical mixing. A mixing proportion per layer and the tilled depths are defined by the user and can very over time.

2.1.3.5. The mass balance process

A mass balance process was introduced in OC-VGEN to account for the changes applied to soil OC and soil particles mass fraction (clay, sand and silt) through different processes. In this approach the model does not exchange the value of each property (*X*), but the changes applied, $\Delta p(X)$, during the time increment, to that property *X* by a given process *p*. Each process will produce a $\Delta \mathrm{p}(X)$ which is an input of the mass balance process. The mass balance process will update the mass of *X*, M_X, and provide the new value whenever it is needed. The module associated to this process is based on equation 9.

$$M_X(t+1) = M_X(t) + \sum_{p=1}^{n} \Delta_p(M_X) \quad (9)$$

where, *t* represents the time step and *n*, number of processes modifying *X*.

2.1.4. OC-VGEN input data requirements, time step and depth discretization

OC-VGEN needs as initial conditions the characteristics of soil corresponding to the distribution of different particle sizes (clay, sand and silt), OC content, bulk density and water content and as boundary conditions the yearly time series of temperature, precipitation and corresponding evapotranspiration as well as land use and vegetation from the four existing land use/vegetation types (agriculture, pasture, coniferous and deciduous woodland).

The time step of the model varies from a few seconds for the case of simulations of water flow, to a day for simulation of OC dynamics, or to a year for application of tillage and bioturbation.

The soil profile is discretized on layers of thickness ranging from few millimeters to few centimeters. In this study we used a fixed layer thickness of 0.05 m down to 1.2 m depth.

2.2 Evaluation data set, forcings and statistical analyses

2.2.1. Evaluation data set

The evaluation dataset consists in soil characteristics collected on three Luvisol plots from a long-term experiment on a Loess deposit, in the Paris Basin, at Mons. All plots were cropped 260 years before present as shown on Cassini maps (Cassini, 1750). Seventy-two years before the sampling date, one of the plots was converted to pasture while the other two experienced differentiated tillage: one plot continued with conventional tillage, the other experienced reduction in tillage depth and intensity over the last 10 years (Table 3). Soil profiles were already extensively characterized by Jagercikova et al. (2014).

2.2.2. Forcing data set

Forcing data consist in climate, NPP, land use and tillage history.

For the spin-up runs, forcing data consist in input fluxes and climate of 1939-1958 period and cultivation with conventional tillage as a land use (Figure 2).

For the 1939-2011 period, forcing data consisted in the land use history of the three above described plots. OC inputs are known for the last 10 years for the two-cropped plots and estimated at 5 until 1970 and then at 4 t ha^{-1} yr^{-1} from 1970 to 2001 (Figure 2c). This decrease in OC inputs was due to an increase of the crop exportation with agriculture intensification in the 70's. For the pasture, they were estimated at 6.7 t ha^{-1} yr^{-1} based on the annual yields estimated by the technical institute for pasture in this region of France. Climate input data were provided by Meteo France for this site (SAFRAN grid; Quintana-Seguí et al., 2008) for the period extending from 1939 to 2011 (Figure 2).

For the 2011-2100 period, two economic scenarios were considered, the RCP 2.6 (greenhouse emissions decreasing after 2020) and RCP8.5 (emissions continue to rise) IPCC scenarios (Vuuren et al., 2011). We used as input climate the bias-corrected outputs produced within the ISI-MIP project (Warszawski et al., 2014) from three Earth System Models (ESM) named the HadGEM, IPSL-CM5A and MIROC-ESM-CH for these two scenarios (Figure 3a, b and c). The NPP was estimated by running the land surface model ORCHIDEE (Krinner et al., 2005) forced by the climate fields of the three ESMs for the two scenarios (RCP 2.6 and RCP8.5). The precipitation variations range from -20 to +50 mm, temperature rise from 2 to 8 ° C and NPP increase from 1 to 2.4 (t C ha^{-1}) depending on the considered scenario and on the selected ESM.

2.3 Data treatment

In order to estimate the impact of formalisms of the three selected processes (root depth distribution, bioturbation and OC depth decomposition) on OC depth distribution we compared, the OC stocks simulated using different formalisms at the end of the simulation. Comparisons are presented in terms of percentage of variations, ΔOC, calculated in Equation 10.

$$\Delta OC = 100 \times \frac{OC_{Alt} - OC_{Ref}}{OC_{Ref}} \tag{10}$$

where OC_{Ref} stands for OC stock in mineral horizons simulated using the reference setting of process formalism in OC-VGEN model (Ref in Table 2) and OC_{Alt}, the OC stock simulated by model versions built based on alternative formalisms (Table 2). Permanent above ground OC layer (ectorganic) when existing (pasture) is considered in the total soil OC stock calculation, but not in OC depth distribution analysis as this layer is not considered to be in the soil profile. We specifically looked into deep OC stocks response to different formalisms or parameters. Below 30 cm, OC stocks are considered as deep OC in this study.

We also compared the OC stocks simulated by the different versions of the model to measurements made on the long-term experiment plots to test the quality of the different version of the model. We estimated the model–measurement discrepancy using statistics of deviation as proposed by Kobayashi and Salam (2000).

The Mean Squared Deviation, MSD (Equation 11) was calculated as well as its three components, being: the squared bias of simulation (Equation 12), the squared difference between standard deviations of simulation and measurements (SDSD – Equation 13) and the lack of positive correlation weighted by the standard deviations (LSC – Equation 14).

$$MSD = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 = (\bar{x} - \bar{y})^2 + \frac{1}{n}\sum_{i=1}^{n}[(x_i - \bar{x}) - (y_i - \bar{y})]^2 \tag{11}$$

$$SB = (\bar{x} - \bar{y})^2 \tag{12}$$

$$SDSD = (SD_s - SD_m)^2 \tag{13}$$

where SD_s is the standard deviation of simulations and SD_m that of measurements.

And finally,

$$LSC = 2SD_sSD_m(1 - r) \tag{14}$$

Where r represents the correlation coefficient between the simulations and measurements being:

$$r = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \acute{x})(y_i - \acute{y})}{SD_sSD_m} \tag{15}$$

The sum of the three component equals the MSD by definition. The lower the value of MSD, the closer the simulation is to the measurement.

3. Results and discussion

3.1 Impact of formalism of key OC depth distribution processes

Simulated total soil OC stocks were as expected affected at the first order by the introduction of a depth-variable decomposition rate coefficient or by a change in the above/below ground fresh organic input for pasture. Other changes in the numerical representation of the processes only affected the OC depth distribution within the soil profile (Table 4). While considering the deep OC stocks (30-120 cm), the introduction of a depth-variable decomposition rate coefficient resulted in an increase of those stocks while other numerical representation changes decreased them (Table 4). While considering the depth distribution in more details (Figure 5), the effect of the different numerical representation of the processes was more complex as described below.

Effect of the root density function **-** In comparison to default rooting function and for the two cropped profiles, the use of Zeng (2001) and Jackson et al. (1996) formalisms increased the OC stocks simulated for the upper soil layers (0 to 35 cm) by 20 % and decreased it below 40 cm, with maximum decrease of 20% around 60 cm (Figure 5 a and b). Zeng (2001) formalism produced slightly higher OC stocks than Jackson et al. (1996) formalism below 70 cm. For pasture, both functions increased the OC stocks above 15 cm depth, with an increase of 20 % for the first soil compartment. This increase was larger and deeper (up to 25 cm) with Jackson et al. (1996) than with Zeng (2001) formalism. Below that depth, both formalism simulated lower OC stocks than the formalism used as a reference (Finke, 2012). When considering Zeng (2001) formalism, this decrease occurred mainly from 15 to 70 cm in depth with a maximum decrease of 10 % around 25 cm, while with Jackson et al. (1996) formalism, the decrease started from 25 cm depth with a maximum of 10 % around 50 cm. In the case of Zeng (2001) formalism, no differences in OC stocks compared to the reference function were recorded below 70 cm (Figure 5b).

The use of conventional diffusive transport of OC for bioturbation instead of a vertical mixing of matter (based on SoilGen2.24, Finke, 2012) increased the OC stocks between 45 and 110 cm depth, with a maximal decrease at 50 cm (by about 20 %), for the three considered plots. For the surface layers (0-40 cm), the impact of the use of conventional diffusive transport of OC by bioturbation instead of a vertical mixing of matter differed between land uses. For agriculture, a OC stock decrease of 5 to 15 % was simulated, while for pasture, this stock was decreased by 30 % for the upper soil layer and then was increased between 10 and 20 by as much as 5 % (Figure 5c).

Effect of the above/below ground ratio of fresh organic carbon input - For pasture, the alternative scenario corresponded to an increase of the below ground contribution while for agriculture it corresponded to a decrease. In the case of pasture, increasing the below ground contribution logically increased the OC stocks over the whole soil profile by 15 to 50 % depending on the considered depth (Figure 5d), with a maximum increase round 10 cm. The total soil OC stocks increased by 23% while the ectorganic layer decreased by 60% (Table 4). For agriculture, reducing the below ground input did not affect the total soil OC stock (Table 4) since both above and below ground inputs are mixed by tillage. However, it increased the OC input to the soil in the tillage layer and conversely decreased the soil OC input by roots. Therefore, a decrease of the OC stock below 40 cm was observed. This decrease was maximal around 50 cm, where the root proportion was still important, and it became lower below that depth as the root abundance decreased. Above 40 cm, the OC stocks increased by 15 % on the entire depth interval for the conventional tillage and by 40 % over the 10 upper centimetres for the reduced tillage plot (Figure 5d).

The introduction of a depth-variable decomposition rate coefficient only influenced the OC depth distribution below 30 cm since the decomposition rate coefficients used above that depth were the same in the reference and OC_DDCoeff models. The exponential decrease with depth of the decomposition rate coefficient increased as expected the OC stocks up to 85 % at around 100 cm depth for all the considered land uses and tillage practices (Figure 5e). Below the bioturbation depth (i.e., 50 cm), models that combine an exponential decrease with depth of both root input (exp-αz, Eq.3) and decay rates (exp-ζz, Eq. 2) result in equilibrium carbon profile following the shape of exp($-\alpha + \zeta$)z. The C profile is further influenced by the variation in soil moisture and clay content of the horizons, and the increasing proportion of IOM. In the studied soils, the parameterization of Equation 2 clearly underestimated the decay rates. Authors do agree that "soil C turnover is reduced at depth beyond what is expected from environmental controls" (Koven et al., 2013; Guenet et al., 2013). The invoked processes are organic matter protection by association with soil minerals (von Lützow et al., 2006; Rasmussen et al., 2018) and priming effect (Shahzad et al., 2018), which act in interaction. Depth *per se* is not a process-based variable explaining these effects, and the relevant variables still have to be determined.

When comparing the different simulation results to measurements, we see that measurements were better reproduced in cropped land, especially when conventional tillage was considered (lowest MSE), then in pasture (Figures 6 and 7). Under cultivation with conventional tillage, the mean bias of the simulation to the OC stock measurements (estimated by the SB indices) was very small except when considering exponential decrease of the decomposition rate coefficients (Figure 7a). The main error was on the ability of the model to reproduce the shape of the data (LCS), except for the reference simulation, the diffusive bioturbation and the exponential decrease of the decomposition rate coefficients. Instead, on those simulations the magnitude of fluctuation among the simulations were furthest from those of measurements (large SDSD). Almost the same trends in the error partitioning (among SB, SDSD and LCS) were observed for cultivation with reduced tillage. The alternative root density functions represented the data better for both conventional and reduced tillage profiles (Figures 7 a and b).

While considering pasture, the error distribution change drastically, errors being mainly due to errors on simulating the magnitude of fluctuation among the measurements (SDSD), secondarily to the mean bias of the simulation of the global OC stocks (SB). The models had however a good ability to reproduce the shape of the data as demonstrated by the small LSC values. At last, increasing the belowground contribution of fresh litter provided the best estimation of the OC stock measurements in the pasture (Figure 7c). The strong difference in the model ability to reproduce the OC total stock between cultivation and pasture can be explained by the parametrization of the RothC module that was the same for the two land uses and better suited for cultivation.

Candidate descriptors for deep C dynamics modelling - By testing alternative formalisms for the three main processes at the origin of soil C profiles (depth distribution of belowground inputs, soil matter transport and decomposition rates, in these soils with no DOC movement), we could assess the respective weight of each formalism on soil C. We can further discuss the relevant variables for a tentative parameterization. Concerning root inputs, the bi-exponential depth distribution of the roots provides a finer representation of inputs when compared with the mono-exponential, and is more in line with the observation of either biomass (Jobbagy and Jackson, 2000), or young carbon (Balesdent et al., 2018). The single exponential would not bring enough C to the deepest layer, and accordingly would explain deep C stocks only if combined with either strongly reduced carbon decay rates at depth, or carbon input through a diffusion/transport coefficient that would be constant over depth (e.g. Elzein and Balesdent, 1995; Koven et al., 2013). For annual crops, the depth distribution of root input at the annual scale should ideally integrate inputs during plant growth (as eqn. 4 does) and not only final root distribution. At the pluri-annual scale and beyond genotypic drivers, soil moisture (Jobbagy and Jackson, 2000; Balesdent et al., 2018), together with CO2 partial pressure and fertilization, would be relevant variables of rooting and rhizodeposition. A mass mixing with an intensity decreasing with depth, as is described by equation 8 or would be by an equivalent matrix of transfer of matter in between soil layers, is also in line with observations. Finally, decay rates decrease with depth, but with a smaller gradient than those tested in the parameterization of equation 2. One relevant variable for decay rate modifier would be the carbon input flux itself, acting by priming effect (Cheng et al., 2014;

Shazhad et al., 2018). Such a choice would not require additional soil input data for modelling. The second category of variables that affect decay rates is the soil mineralogy expressed either as a weathering indice (Finke et al., 2018), or as secondary minerals (Rasmussen et al., 2017). Soil classification can stand for a proxy of mineralogical properties and may be used to constrain decay rates (Batjes, 2014; Mathieu et al., 2015). But soil mineralogy is not static (Basile-Doelsch et al., 2015), and may evolve gradually with pedogenesis (Finke et al., 2018). This evolution of minerals naturally drove the build-up of the slow component of SOM over the Holocene, but may also be very rapid under man's pressure: agriculture alkalinize acidic soils by liming, or reversely acidify soils by N-fertilization and removal of bases (Guo et al., 2013); global N deposition as well acidifies world soils. Due to these major interactions between the dynamics of carbon and minerals, coupled model of carbon and pedogenesis as proposed in this study represent a step forward. According to the variables we listed, it is furthermore expected that future carbon depth distribution will be affected by changes in landuse, precipitation and NPP.

3.2 Impact of climate, land use and agricultural practices on OC depth distribution: variability among OC-VGEN settings

3.2.1 Impact of land use and agricultural practice change on soil OC storage

Agriculture with conventional tillage was used for the spin up scenario thus considered as a reference scenario in this analysis. While simulating 72 years of this land use, small oscillations of climate and C inputs as well as a change of ploughing depth from year 2000 occurred. These small changes resulted in small fluctuations of the total OC stock observed whatever the considered formalisms or parameters (Figure 8a). While considering deep OC stocks, the different simulations started to deviate from year 2000 (Figure 8d), most probably due to the more superficial ploughing depth that was applied from that date. For deep OC stocks, the reference model and diffusive bioturbation simulations followed the trend observed for the total OC stocks. The alternative above/below ground organic input and the alternative root density function models decreased those stocks by 3.5 % and 2.5 % respectively. The depth dependent decomposition rate coefficient simulated a 2.6 % increase of deep OC stocks compared to the reference model. These evolutions are in agreement with the results discussed in the previous section. The depth dependent decomposition rate coefficient increased the OC depth accumulation and thus counteracted the effect of the shallower ploughing on the OC input to the soil. On the opposite, the decrease of the above/belowground ratio of fresh organic matter and the change of root ground formalisms decreased the deep OC stocks.

For 10 years of reduced tillage (from year 2000), no differences with the conventional tillage were simulated for the total OC stocks (Figure 8b), while, when considering only deep OC, the deviation among different models became more pronounced. The deep OC stocks simulated by the model with depth dependent decomposition rate coefficient followed more or less the same trend as the total OC stocks, while, for all the other simulations, the deep OC stocks decreased from years after 2000. This decrease reached 3 % by the year 2011 for the reference and diffusive bioturbation models, 5 % for the alternative root growth formalisms and up to 10 % for the increased above/below ground input model (Figure 8e). These results showed that a further shallowing of the ploughing depth increased the trends observed after the year 2000 in the case of the agriculture with conventional tillage. Reduced tillage did not increase the total OC stock compared to conventional tillage. While considering the upper 30 cm, a slight increase ranging from 0 to 9 % was observed. Most experiments on reduced tillage in the literature were conducted on durations ranging from 0 to 15 years and thus comparable to the experiment considered in this study. Recent meta-analysis (Baker et al., 2007; Bai et al., 2018) described no significant change in total OC stock with reduced tillage but a change in soil OC distribution comparable to that obtained in this study. Dimassi et al. (2014) attributed this difference to differences in soil climate (water content notably) due to the tillage practices. Our modelling approach could not reproduce such a difference in soil climate due to tillage reduction; the observed changes in OC stocks were mainly due to change in mixing depth and intensity.

For pasture, all the simulations resulted in an increase of 30 to 40 % of total OC stocks after 72 years (Figure 8 c). This increase was more marked while considering the upper 30 cm OC stock with an increase ranging from 60 to 90% depending on the model considered. Poeplau et al. (2011) estimated a 100 ± 20% increase in upper 30 cm stock of soils after grassland establishment in temperate regions while the Guo and Gifford (2002) meta-analysis, depicted only a 19% increase. Our modelling approach provided a value closer to that of Poeplau et al. (2011). For deep OC stocks (30-120 cm), the situation was more complex. Only the decrease of above ground input simulated an increase of the deep OC stock by about 15 %. The reference model as well as diffusive bioturbation and depth dependent decomposition rate coefficient models simulated no changes of deep OC stocks over the 72 years. Finally, both alternative root density function models simulated a decrease in deep OC stocks ranging from 3 to 7 % after 72 years, the largest decrease being, as expected, for the Jackson et al (1996) formalism (Figure 8f).

3.2.2 Impact of two climate change scenarios by the years 2100 on the soil OC storage simulations for three different land use and agricultural practice modalities

For cropped profiles, all of the considered formalisms/parametrisations simulated an increase of the total OC storage ranging from 0 to 3 % at the year 2100 (Figures 9 a and b) and up to the 6 % for the depth dependent decomposition rate coefficient simulation. No significant differences (<2 %) were observed between conventional and reduced tillage in terms of simulated OC stocks. For the pasture, the simulations predicted a larger total OC stock increase ranging from 9 to 11% at the year 2100 (Figure 9c).

Considering the two IPCC scenarios, the standard deviation of the simulated OC stocks between RPC8.5 and RPC2.5 ranged from 0 to 3 %, as for cropland, whatever the considered model version.

For deep OC stocks (30-120cm), the situation was once again more complex. The increase of above/below ground ratio of fresh organic input leaded to a decrease of the deep OC stock by 4 and 11 % for conventional and reduced tillage respectively, as well as the use of an alternative root density function (Zeng, 2001) although to a lesser extent (3 % for both plots). In contrast, the model with depth dependent decomposition rate coefficients increased the deep OC stock to a maximum of 8 % for both cropped plots. The reference model and diffusive bioturbation did not induce a significant change over the simulated period. On cropped profiles, the variations of deep OC stocks related to the formalisms/ parameters used in the model were larger than that of total OC stocks (Figures 9d and e) and were more marked for shallower tillage, while the effect of IPCC scenarios stayed in the range of 3 %. For pasture, most of the simulations predicted an increase in deep OC stocks, with the exception of the simulation with Jackson et al. (1996)'s root density function that resulted in a slight decrease of the deep OC stock. The maximum increases of 6 to 9 % for PRC2.6 and RPC8.5 respectively were simulated by the model with higher below ground fresh organic input (Figure 9f). The effect of IPCC scenarios again produced changes in the deep OC stocks ranging from 0 to 3 %.

Thus, regardless of the land use or tillage practices, variabilities in the simulated total OC stocks induced by different soil process formalisms/parameters and by the different forcing scenarios (RPC8.5 and RPC2.6) were of same order of magnitude (Figures 9a to c). When considering the deep OC stocks (30-120 cm), the variability induced by the choice of processes/formalisms used was dominant (Figures 9d to f), showing that efforts on calibrating the deep OC transfer processes are needed.

Other studies projecting OC stocks over the 21st century only considered the upper 30 cm of the soil (e.g., Smith et al., 2005; Lugato et al., 2014; Wiesmeier et al., 2016). In this study, by introducing new soil processes and the uncertainty related to their knowledge, we showed that the simulated behaviour of deep OC differs substantially from that of top soil OC stocks. We showed that while for the total OC stocks (as well as top 30 cm OC stocks) an increase could be projected considering the suggested climate change scenarios; both an increase and a decrease in deep OC stock are possible over the coming century depending on the formalism/parameter considered in the simulation.

Conclusion

In this paper, we proposed the first fully modular OC depth distribution model, called OC-VGEN that was shown to be efficient for testing the effect of different numerical representations soil processes on OC depth distribution. We demonstrated that the OC-VGEN model include processes that are crucial at a decadal to a century time scale for modelling soil OC stock evolution in Luvisols, notably explicit transfer of water and temperature although only partially for water transfer that remains only indirectly taken into consideration since soil moisture deficit is not directly derived from soil water content at different depths. In addition, transfer of DOC was not considered in this model, since DOC is negligible in the type of soil considered. Nevertheless this process should be added if other soil types as podzols for which this process is dominant had to be modelled. The development of the model under the VSoil modelling plateform should ease this implementation.

For the numerical representations tested, namely root depth distribution, bioturbation and OC decomposition rate coefficients, we showed that the simulated OC depth-distribution (below 30 cm) was very dependent on the tested formalisms/parameters, while the total soil OC stocks was not. We showed that the use of different soil processes formalisms/parameters had a larger impact on deep OC stock prediction than that of forcing scenarios tested. These forcing scenarios were nevertheless chosen as the extreme cases in the range of possibilities for both land use and climate change. These results demonstrate the need of further calibration of soil processes responsible for the building of deep OC stock in soils. These first results strongly suggest the need for a bioturbation process progressively decreasing with depth and decay rates also decreasing with depth, but with a smaller gradient than the one tested.

We proposed here a first modelling approach for OC stock estimation considering most soil processes and their feedbacks. Our study demonstrated that, due to a limited knowledge, considering soil processes added a lot of uncertainties on the soil OC stock projections, notably for the deep soil OC, and thus more effort should be done in evaluating the most reasonable combination of formalisms for soil processes and their parametrization. To do so, this work should be extended to different soil types under different climates in which the hierarchy of the processes could be different, thus allowing better conclusions on the formalisms to be chosen for the different soil processes. Future research with models such as OC-VGEN should especially focus on the above to below ground fresh organic input ratio and on depth-dependent OC decomposition rate coefficients, since OC-VGEN is the most sensitive to these formalisms/parameters. Combining modelling and isotopic tracing approaches, by introducing the isotopes in the models could allow overcoming this limit.

Acknowledgement

This research was conducted in the framework of the Agriped project (ANR-10-BLANC-605) and the DeDyCas project (ANR 14-CE01-0004) supported by the French National Research Agency (ANR) and the ASSESS project (ERANETMED2-72-209 ASSESS).

S. Keyvanshokouhi received a PhD grant from the French National Institute for Agricultural Research (INRA) and the French agency for environment and energy (ADEME). The authors are grateful to INRA of Mons-en-Chaussee (France) for providing the access to their long-term experimental site and the associated data, to B. Davis for supplying reconstructed temperature and precipitation time series, to Meteo France for providing climatic data from the SAFRAN Grid for the studied site.

References

Bai, Z., Caspari, T., Ruiperez Gonzalez, M., Batjes , N.H., Mäder, P., Bünemann, E.K, de Goede, R., Brussaard, L., Xu, M., Santos Ferreira, C.S., Reintam, E., Fan, H., Mihelič, R., Glavan, M., Tóth, Z., 2018. Effects of agricultural management practices on soil quality: A review of long-term experiments for Europe and China. Agriculture, Ecosystems & Environment, 265, 1-7.

Baisden, W. T., Amundson, R., Brenner, D. L., Cook, A. C., Kendall, C., Harden, J. W., 2002. A multiisotope C and N modeling analysis of soil organic matter turnover and transport as a function of soil depth in a California annual grassland soil chronosequence. Global Biogeochemical Cycles, 16, 1135. doi:10.1029/2001GB001823

Baker, J. M., Ochsner, T. E., Venterea, R. T., Griffis, T. J., 2007. Tillage and soil carbon sequestration-What do we really know? Agriculture, Ecosystems and Environment, 118, 1-5. doi:10.1016/j.agee.2006.05.014

Balesdent, J., Basile-Doelsch, I., Chadoeuf, J., Cornu, S., Derrien, D., Fekiacova, Z., Hatté, C, 2018. Atmopshere-soil carbon transfer as a function of soil depth. Nature, 559, 599–602. doi:10.1038/s41586-018-0328-3

Basile-Doelsch, I., Balesdent, J., Rose, J. 2015. Are interactions between organic compounds and nanoscale weathering minerals the key drivers of carbon storage in soils? Environmental Science & Technology 49, 3997−3998

Batjes, N., 2014. Total carbon and nitrogen in the soils of the world. European Journal of Soil Science, 65, 4-21.

Boizard, H., Yoon, S. W., Leonard, J., Lheureux, S., Cousin, I., Roger-Estrade, J., Richard, G., 2013. Using a morphological approach to evaluate the effect of traffic and weather conditions on the structure of a loamy soil in reduced tillage. Soil and Tillage Research, 127, 34-44. doi:10.1016/j.still.2012.04.007

Braakhekke, M. C., Beer, C., Hoosbeek, M. R., Reichstein, M., Kruijt, B., Schrumpf, M., Kabat, P., 2011. SOMPROF: A vertically explicit soil organic matter model. Ecological Modelling, 222, 1712-1730. doi:10.1016/j.ecolmodel.2011.02.015

Brimo, K., Garnier, P., Lafolie, F., Séré, G., Ouvrard, S., 2018. In situ long-term modeling of phenanthrene dynamics in an aged contaminated soil using the VSOIL platform. Science of the Total Environment, 619–620, 239–24.

Camino-Serrano, M., Guenet, B., Luyssaert, S., Janssens, I. A. 2018. ORCHIDEE-SOM: Modeling soil organic carbon (SOC) and dissolved organic carbon (DOC) dynamics along vertical soil profiles in Europe. Geoscientific Model Development 11, 937-957.

Campbell, E. E., Paustian, K., 2015. Current developments in soil organic matter modeling and the expansion of model applications: a review. Environmental Research Letters, 10, 123004. doi:10.1088/1748-9326/10/12/123004

Canadell, J., Jackson, R. B., Ehleringer, J. B., Mooney, H. A., Sala, O. E., Schulze, E.-D., 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia, 108, 583-595. doi:10.1007/BF00329030

Cannavo, P., Lafolie, F., Nicolardot, B., Renault, P., 2006. Modelling seasonal variations in CO_2 and N2O concentrations with a model describing C and N behaviour in the vadose zone. Vadoze Zone Journal, 5, 990-1004.

Cassini, C. F., 1750. Composite: Carte de France. Carte de France. Levee par ordre du Roy. Retrieved from http://www.davidrumsey.com/xmaps10000.html

Cheng, W., Parton, W. J. ,Gonzalez-Meler, M. A., Phillips, R., Asao, S., McNickle, G. G., Brzostek, E., Jastrow, J. D. 2014, Synthesis and modeling perspectives of rhizosphere priming. New Phytol. 2014 Jan;201(1):31-44. doi: 10.1111/nph.12440.

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

Davidson, J., Graetz, D., Rao, P., Selim, H., 1978. Simulation of nitrogen movement, transformation and uptake in plant root zone. (1978, Ed.)

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.-P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agriculture, Ecosystems & Environment, 188, 134-146. doi:10.1016/j.agee.2014.02.014

Elzein, A., Balesdent, J., 1995. Mechanistic Simulation of Vertical Distribution of Carbon Concentrations and Residence Times in Soils. Soil Science Society of America Journal, 59, 1328-1335. doi:10.2136/sssaj1995.03615995005900050019x

Finke, P. A., 2012. Modeling the genesis of luvisols as a function of topographic position in loess parent material. Quaternary International, 265, 3-17. doi:10.1016/j.quaint.2011.10.016

Finke, P. A., Hutson, J. L., 2008. Modelling soil genesis in calcareous loess. Geoderma, 145, 462-479. doi:10.1016/j.geoderma.2008.01.017

Finke, P., Opolot, E., Balesdent, J., Berhe, A. A., Boeckx, P., Cornu, S., Harden, J., Hatté, C., Williams, E., Doetterl, S.. 2018. Can SOC modelling be improved by accounting for pedogenesis? Geoderma, accepted.

Gale, M. R., Grigal, D. F., 1987. Vertical root distributions of northern tree species in relation to successional status. Canadian Journal of Forest Research, 17, 829-834. doi:10.1139/x87-131

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

Guo, J. H., Liu, X.J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., Christie, P., Goulding, K. W. T., Vitousek, P. M., Zhang, F. S., 2010. Significant Acidification in Major Chinese Croplands Science, 327,1008-1010

Guo, L. B., Gifford, R. M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology, 8, 345-360. doi:10.1046/j.1354-1013.2002.00486.x

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., Jørgensen, H.B., Isberg, P.-E., 2016. How does tillage intensity affect soil organic carbon? A systematic review protocol. Environmental Evidence, 5, 1-1. doi:10.1186/s13750-016-0052-0

He, Y., Trumbore, S.E, Torn, M.S., Harden, J.W., Vaughn, L.J.S., Allison, S.D., Randerso, J.T., 2016. Radiocarbon constraints imply reduced carbon uptake by soils during the 21st century. Science 353, 1419-142.

Hilinski TE (2001) 'Implementation of exponential depth distribution of organic carbon in the CENTURY Model. CENTURY soil organic matter model user's manual.' (Department of Soil and Crop Sciences, Colorado State University: Fort Collins, CO).

Hutson, J. L., 2003. Leaching Estimation and Chemistry Model: A Process-Based Model of Water and Solute Movement, Transformations, Plant Uptake, and Chemical Reactions in the Unsaturated Zone. Department of Crop and Soil Sciences, Cornell University, Ithaca.

Jackson, R. B., Canadell, J., Ehleringer, J. R., Mooney, H. A., Sala, O. E., Schulze, E. D., 1996. A global analysis of root distributions for terrestrial biomes. Oecologia, 108, 389-411. doi:10.1007/BF00333714

Jagercikova, M., Evrard, O., Balesdent, J., Lefèvre, I., Cornu, S., 2014. 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 and Tillage Research, 140, 82-97. doi:10.1016/j.still.2014.02.013

Janik, L., Spouncer, L., Correll, R., Skjemstad, J., 2002. Sensitivty analysis of the RothC carbon model. National Carbon Accounting System technical report; No. 30. ISSN: 14426838

Jarvis, N. J., Taylor, A., Larsbo, M., Etana, A., Rosén, K., 2010. Modelling the effects of bioturbation on the re-distribution of ^{137}Cs in an undisturbed grassland soil. European Journal of Soil Science, 61, 24-34. doi:10.1111/j.1365-2389.2009.01209.x

Jenkinson, D. S., Coleman, K., 2008. The turnover of organic carbon in subsoils. Part 2. Modelling carbon turnover. European Journal of Soil Science, 59, 400-413. doi:10.1111/j.1365-2389.2008.01026.x

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

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

Krinner, G., Viovy, N., Noblet, N., Friedlingstein, P., Ciais, P., 2002. A dynamical global vegetation model for studies of the coupled atmosphere-biosphere system. Global Biogeochemical Cycles, 19(GB1015), 1 - 44. DOI: 10.1029/2003GB002199

Lafolie, F., Cousin, I., Marron, P.-A., Mollier, A., Pot, V., Moitrier, Ni., Moitrier, Na, Nouguier, C., 2014. The "VSOIL" modeling platform. Rev. For. Fr. LXVI, hors série 2014 (2014) (ISSN 0035) https://doi.org/10.4267/2042/56287

Lal, R., 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. Science, 304, 1623-1627. doi:10.1126/science.1097396

Lorenz, K., Lal, R., 2005. The Depth Distribution of Soil Organic Carbon in Relation to Land Use and Management and the Potential of Carbon Sequestration in Subsoil Horizons. Advances in Agronomy, 88, 35-66. http://www.sciencedirect.com/science/article/pii/S0065211305880022

Lugato, E., Panagos, P., Bampa, F., Jones, A., Montanarella, L., 2014. A new baseline of organic carbon stock in European agricultural soils using a modelling approach. Global Change Biology, 20, 313-326. doi:10.1111/gcb.12292

Luo, Y., Ahlström, A., Allison, S.D., Batjes, N.H., Brovkin, V., Carvalhais, N., Chappell, A., Ciais, P., Davidson, E.A., Finzi, A., Georgiou, K., Guenet, B., Hararuk, O., Harden, J.W., He, Y., Hopkins, F., Jiang, L., Koven, C., Jackson, R.B., Jones, C.D., Lara, M.J., Liang, J., McGuire, A.D., Parton, W., Peng, C., Randerson, J.T., Salazar, A., Sierra, C.A., Smith, M.J., Tian, H., Todd-Brown, K.E.O., Torn, M., van Groenigen, K.J., Wang, Y.P., West, T.O., Wei, Y., Wieder, W.R., Xia, J., Xu, X., Xu, X., Zhou, T., 2016. Toward more realistic projections of soil carbon dynamics by Earth system models. Glob. Biogeochem. Cycles, 30, 40–56, doi:10.1002/2015GB005239

von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions – a review. European Journal of Soil Science, 57, 426-445. doi:10.1111/j.1365-2389.2006.00809.x

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.C, Vågen, T.G., van Wesemael, B., Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma, 292, 59-86. doi:10.1016/j.geoderma.2017.01.002

Montagne, D., Cornu, S., Le Forestier, L., Hardy, M., Josière, O., Caner, L., Cousin, I., 2008. Impact of drainage on soil-forming mechanisms in a French Albeluvisol: Input of mineralogical data in mass-balance modelling. Geoderma, 145, 426-438. doi:10.1016/j.geoderma.2008.02.005

Nakane, K., 1978. A Mathematical Model of the Behavior and Vertical Distribution of Organic Carbon in Forest Soils: II. a Revised Model Taking the Supply of Root Litter into Consideration. Japanese Journal of Ecology, 28, 169-177. doi:10.18960/seitai.28.3_169

Parton, W. J., 1996. The CENTURY model. In Evaluation of Soil Organic Matter Models, pp. 283-291. Springer, Berlin, Heidelberg. Retrieved from https://link.springer.com/chapter/10.1007/978-3-642-61094-3_23

Paustian, K., Andrén, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., Tiessen , H., Van Noordwijk , M., Woomer, P. L., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use and Management, 13, 230-244. doi:10.1111/j.1475-2743.1997.tb00594.x

Poeplau, C., Don, A., Vesterdal, L., Leifeld, J., Van Wesemael, B., Schumacher, J., Gensior, A., 2011. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. Global Change Biology, 17, 2415-2427. doi:10.1111/j.1365-2486.2011.02408.x

Post, W. M., Kwon, K. C., 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology, 6, 317-327. doi:10.1046/j.1365-2486.2000.00308.x

Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, MCanellas , C., Franchisteguy , L., Morel, S., 2008. Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France. Journal of Applied Meteorology and Climatology, 47, 92-107. doi:10.1175/2007JAMC1636.1

Rasmussen, C., Heckman, K., Wieder, W.R., Keiluweit, M., Lawrence, C.R., Berhe, A.A., Blankinship, J.C., Crow, S.E., Druhan, J.K, Hicks Pries, C.E., Marin-Spiotta, E., Plante, A.F., Schädel, C., Schimel, J.P., Sierra, C.A., Thompson, A., Wagai, R., 2018. Beyond clay: towards an improved set of variables for predicting soil organic matter content. Biogeochemistry 137 (3): 297-306. https://doi.org/10.1007/s10533-018-0424-3

Riley, W. J., Maggi, F., Kleber, M., Torn, M. S., Tang, J. Y., Dwivedi, D., Guerry, N., 2014. Long residence times of rapidly decomposable soil organic matter: application of a multi-phase, multi-component, and vertically resolved model (BAMS1) to soil carbon dynamics. Geosci. Model Dev., 7, 1335-1355. doi:10.5194/gmd-7-1335-2014

Shahzad, T., Rashid, M. I., Maire, V., Barot, S., Perveen, N., Alvarez, G., Mougin C., Fontaine, S. 2018 Root penetration in deep soil layers stimulates mineralization of millennia-old organic carbon. Soil Biol. Biochem., 124, 150-160. https://doi.org/10.1016/j.soilbio.2018.06.010

Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080. Global Change Biology, 11, 2141-2152. doi:10.1111/j.1365-2486.2005.001075.x

Smith, P., Fang, C., Dawson, J. J., Moncrieff, J. B., 2008. Impact of Global Warming on Soil Organic Carbon. Advances in Agronomy, 97, 1-43. http://www.sciencedirect.com/science/article/pii/S0065211307000016

Tonneijck, F. H., Velthuis, M., Bouten, W., Van Loon, E. E., Sevink, J., Verstraten, J. M., 2016. The effect of change in soil volume on organic matter distribution in a volcanic ash soil. European Journal of Soil Science, 67, 226-236. doi:10.1111/ejss.12329

Vuuren, P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Climatic Change, 109, 5-31. doi:10.1007/s10584-011-0148-z

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., Schewe, J., 2014. The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework. Proceedings of the National Academy of Sciences of the United States of America, 111, 3228-3232. doi:10.1073/pnas.1312330110

Wiesmeier, M., Poeplau, C., Sierra, C. A., Maier, H., Frühauf, C., Hübner, R., Kühnel, A., Spörlein, P., Geuß, U., Hangen, E., Schilling, B., von Lützow, M., Kögel-Knabner, I., 2016. Projected loss of soil organic carbon in temperate agricultural soils in the 21st century: effects of climate change and carbon input trends. Scientific Reports, 6. doi:10.1038/srep32525

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma, 90, 169–185.

Xu, X., Liu, W., Kiely, G., 2011. Modeling the change in soil organic carbon of grassland in response to climate change: Effects of measured versus modelled carbon pools for initializing the Rothamsted Carbon model. Agriculture, Ecosystems & Environment, 140, 372-381. doi:10.1016/j.agee.2010.12.018

Zeng, X., 2001. Global Vegetation Root Distribution for Land Modeling. Journal of Hydrometeorology, 2, 525-530. doi:10.1175/1525-7541(2001)002%3C0525:GVRDFL%3E2.0.CO;2

Figure captions

Figure 1: Processes involved in the OC depth distribution and the feedbacks between them. DPM: decomposable plant material, RPM: resistant plant material, BIO: biomass, HUM: humus, and IOM: inert organic matter.

Figure 2: Forcing scenarios for the past reconstruction and the spin-up a) precipitation, b) mean temperatures, and c) organic carbon inputs for different land-use and tillage histories. The period ranging from 1940 to the vertical dashed line was used as spin up scenario.

Figure 3: Forcing scenarios for the climate change scenarios over the coming century: anomalies of a) precipitation, b) average temperature obtained with climatic data produced by HadGEM (H), IPSL-CM5A (I) and MIROC-ESM-CH (M) Earth System Models and c) net primary production (NPP) produced by ORCHIDEE. Code 2.6 is used to represent the RCP 2.6 scenarios (greenhouse emissions decreasing after 2020) and 8.5 to represent RCP 8.5 scenarios (emissions continue to rise).

Figure 4: General layout of the simulations.

Figure 5: Differences of simulated OC depth distribution between the reference model and the alternative formalisms/parameters for conventional tillage (M1), reduced tillage (M2) and pasture (M3): a) Jackson et al. (1996) rooting density function, b) Zeng. (2001) rooting density

function, c) bioturbation, d) above/below ground fresh organic input, and e) depth dependent decomposition rate coefficient.

Figure 6: Simulated OC depth distribution in 2011 by the 6 different versions of OC-VGEN model based different formalisms/parameters and measurements for a) the conventional tillage (M1), b) the reduced tillage (M2), and c) the pasture (M3) profiles. Segmented line with error bars depict the measurements and the associated uncertainties. For description of formalism scenarios see Table 2. Units are t C ha^{-1} per 5 cm-thick layer.

Figure 7: Mean square deviation (MSD) and its components, namely square bias (SB), squared difference between standard deviations (SDSD) and lack of correlation weighted by the standard deviation (LCS) for the OC depth distributions simulated by the 6 model versions compared to measurements for a) conventional tillage (M1), b) reduced tillage (M2) and c) pasture (M3).

Figure 8: Simulated soil OC stock change relative to the initial stock over 72 years, considering 6 soil process formalisms and parameters. a) and d) represent continuous conventional tillage (M1); b) and e) reduced tillage (M2) and c) and f) pasture (M3). Change in the total OC stock is shown in a), b) and c) and in stock below 30 cm in d), e) and f). For description of the formalisms, see Table 2.

Figure 9: Projection of the total soil OC stock over the coming century considering 6 climatic scenarios and 7 OC-VGEN versions differing by their formalism/parameter. a) and d) represent conventional tillage, b) and e) reduced tillage and c) and f) pasture . Blue lines represent the RCP2.6 IPCC climatic scenario and red lines represent the RCP8.5 IPCC climatic scenario for all

the three Earth System Models. For description of the formalisms, see Table 2. Lines represents the average of the three climatic model for each climatic scenario and the coloured areas represent the bandwidths of the simulation results of the three climatic model for a given climatic scenario.

Table captions

Table 1: List of the major processes and corresponding modules used to build OC-VGEN model inside VSoil platform. Some of them were used from the official inventory of VSoil platform (highlighted), while other had to be created either based on modules pre-existing in the literature or completely newly designed (bold).

Table 2: Summary of the scenarios of the different numerical representations (formalisms and parameters) tested on the three Luvisol profiles of pasture and cropped land with conventional and reduced tillage.

Table 3: Description of the study site. M1, M2 and M3 stands for the three studied plots in Mons.

Table 4: OC stocks (t ha-1) simulated at the end of the 72 years simulations with different soil processes formalisms/parameters in OC-VGEN for the three experimental plots.

Table 1: List of the major processes and corresponding modules used to build OC-VGEN model inside VSoil platform. Some of them were used from the official inventory of VSoil platform (highlighted), while other had to be created either based on modules pre-existing in the literature or completely newly designed (bold).

Process		**Module**	**Original model**	**Reference**
Organic matter dynamics		Exponential decay of OC pools	RothC-26.3	Coleman et al. (1997)
Water, gaz and heat transport	Gas transport and balance	Convection-diffusion equation	PASTIS	Cannavo et al. (2006)
	Heat transport and balance	Convection-diffusion equation	PASTIS	Cannavo et al. (2006)
	Water flow and balance	Richard's equation	PASTIS	Cannavo et al. (2006)
	Change in soil hydraulic properties	Hypres pedotransfer function	SoilGen	Finke (2012) after Wösten et al. (1999)
	Water runoff	Removing excess water	LEACHC	Hutson (2003)
Plant development	Plant development	Input file	SoilGen	Finke (2012)
	OC matter input to the ground	Input file	SoilGen	Finke (2012)
	Root development	Exponential root growth	SoilGen	Finke and Hutson (2008)
	Root water uptake		LEACHC	Hutson (2003)
Solid vertical mixing	Bioturbation	Vertical mixing + compartment homogenization	SoilGen	Finke and Hutson (2008)
	Tillage practices	Vertical mixing + compartment homogenization	SoilGen	Finke and Hutson (2008)
Solid mineral balance		**Balancing soil characteristics**	**OC-VGEN**	**This study**

Table 2: Summary of the scenarios of the different numerical representations (formalisms and parameters) tested on the three Luvisol profiles of pasture and cropped land with conventional and reduced tillage.

Scenario name	Land use	Root depth distribution (RDF)	Above/below ground fresh OC ratio	Bioturbation	Decomposition coefficient
Reference setting -Ref	Crop	$RDF(z,t) = R_{max}(t)\, exp(-\beta z^2)\, cos\,\frac{\pi z}{2L(t)}$	41/59	Mixing model after SoilGen2.24	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z)$
	Pasture	$RDF(z) = \alpha . e^{-\alpha z}$	58/42		
Alt 1 - RD_Jackson	Crop	$RDF(z) = -ln(\beta).\beta^z$	41/59	Mixing model after SoilGen2.24	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z)$
	Pasture		58/42		
Alt 2 - RD_Zeng	Crop	$RDF(z) = \frac{1}{2}\,(a.e^{-az} + b.e^{-bz})$	41/59	Mixing model after SoilGen2.24	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z)$
	Pasture		58/42		
Alt 3 - RD_A/B	Crop	$RDF(z,t) = R_{max}(t)\, exp(-\beta z^2)\, cos\,\frac{\pi z}{2L(t)}$	90/10	Mixing model after SoilGen2.24	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z)$
	Pasture	$RDF(z) = \alpha . e^{-\alpha z}$	22/78		
Alt 4 - OC_DDCoeff	Crop	$RDF(z,t) = R_{max}(t)\, exp(-\beta z^2)\, cos\,\frac{\pi z}{2L(t)}$	41/59	Mixing model after SoilGen2.24	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z) r_z(z)$
	Pasture	$RDF(z) = \alpha . e^{-\alpha z}$	58/42		
Alt 5 - Bioturb	Crop	$RDF(z,t) = R_{max}(t)\, exp(-\beta z^2)\, cos\,\frac{\pi z}{2L(t)}$	41/59	$\frac{\partial\, M_{OC}\,(z,t)}{\partial t} = D(z) \frac{\partial^2 M_{OC}\,(z,t)}{\partial z^2}$	$K(z) = K_{0,p} r_T(z) r_{Wt}(z) r_{SC}(z)$
	Pasture	$RDF(z) = \alpha . e^{-\alpha z}$	58/42		

Table 3: Description of the study site. M1, M2 and M3 stands for the three studied plots in Mons.

Site		**Mons**
Coordinates		40° 52'01" N – 3° 01'53" E
Elevation		88 m
Mean annual rainfall		680 mm
Mean annual temperature		11°C
History of land use		M1&M2: wheat-corn-sugar beet M3: pasture since 1939
History of agricultural practices for cultivated plots	Liming	Not since 1986 under cultivation and 1939 for pasture
	Fertilisation	M1&M2: data available since 1970 M3: no fertilization since 1939
	Tillage	M1: conventional tillage since 2001 M2: reduced tillage since 2000 sine 2001 M3: last tillage in 1939

Table 4: OC stocks (t ha^{-1}) simulated at the end of the 72 years simulations with different soil processes formalisms/parameters in OC-VGEN for the three experimental plots.

Soil depth in cm	**Formalism/parameter**	**Land use**		
		Agriculture		Pasture (M3)
		conventional tillage (M1)	reduced tillage (M2)	
Ecto-organic layer		Initial stock: 0		
		0	0	22
		0	0	22
		0	0	22
		0	0	9
		0	0	21
		0	0	22
0-120		Initial stock: 84		
	Ref	85	85	87
	RD_Jackson	85	86	87
	RD_Zeng	85	86	88
	RD_A/B	84	86	107
	OC_DDCoeff	106	107	110
	Bioturb	84	85	85
30-120		Initial stock: 50		
	Ref	45	44	41
	RD_Jackson	39	39	39
	RD_Zeng	40	39	40
	RD_A/B	38	36	47
	OC_DDCoeff	69	68	64
	Bioturb	47	46	43

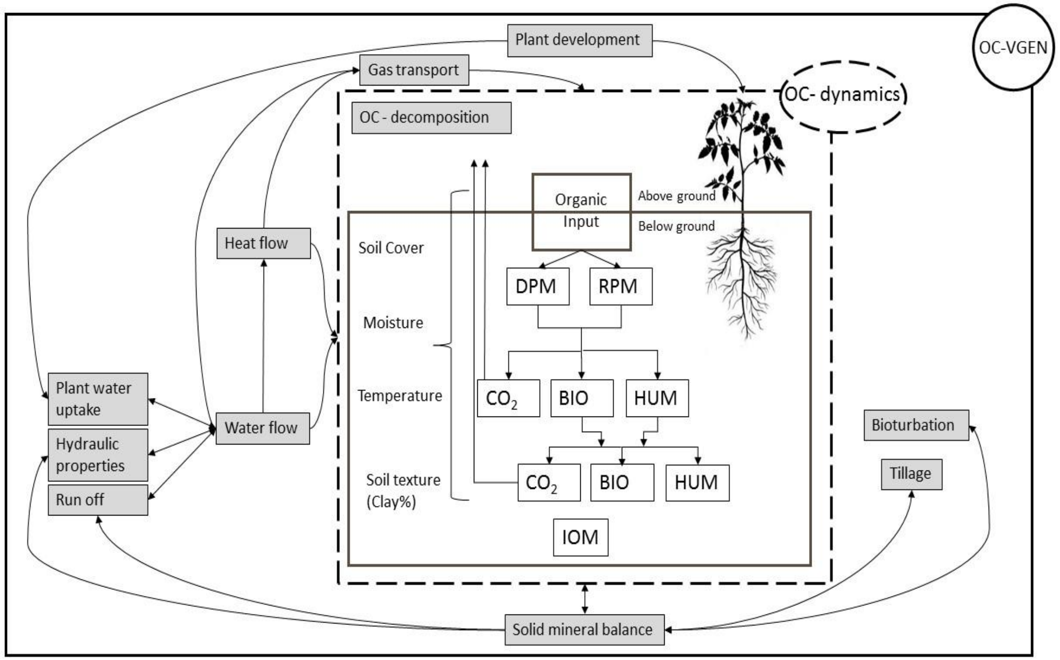


Figure 1: Processes involved in the OC depth distribution and the feedbacks between them. DPM: decomposable plant material, RPM: resistant plant material, BIO: biomass, HUM: humus, and IOM: inert organic matter.

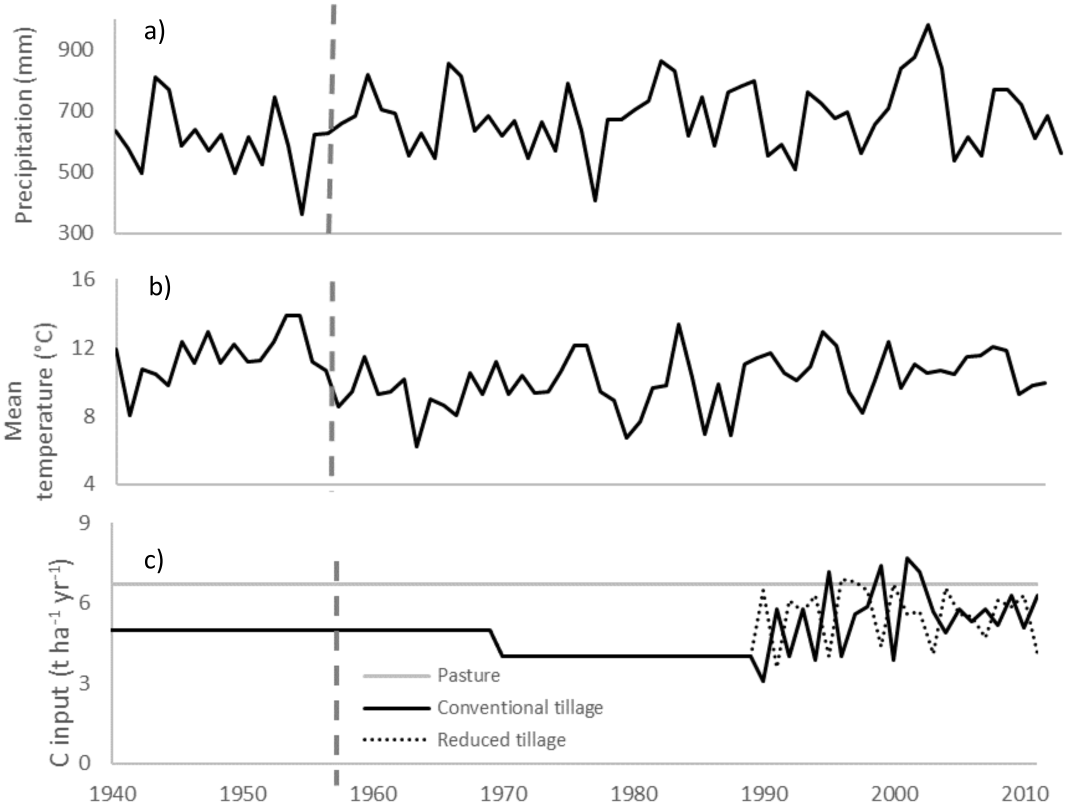


Figure 2: Forcing scenarios for the past reconstruction and the spin-up a) precipitation, b) mean temperatures, and c) organic carbon inputs for different land-use and tillage histories. The period ranging from 1940 to the vertical dashed line was used as spin up scenario.

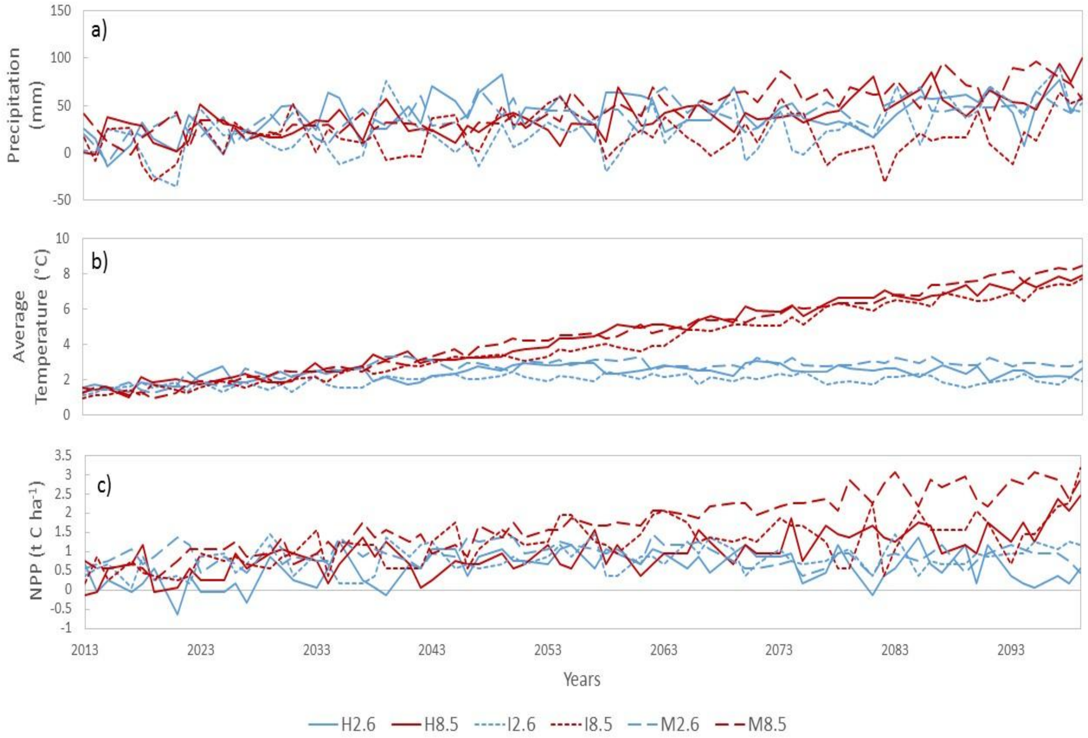


Figure 3: Forcing scenarios for the climate change scenarios over the coming century: anomalies of a) precipitation, b) average temperature obtained with climatic data produced by HadGEM (H), IPSL-CM5A (I) and MIROC-ESM-CH (M) Earth System Models and c) net primary production (NPP) produced by ORCHIDEE. Code 2.6 is used to represent the RCP 2.6 scenarios (greenhouse emissions decreasing after 2020) and 8.5 to represent RCP 8.5 scenarios (emissions continue to rise).

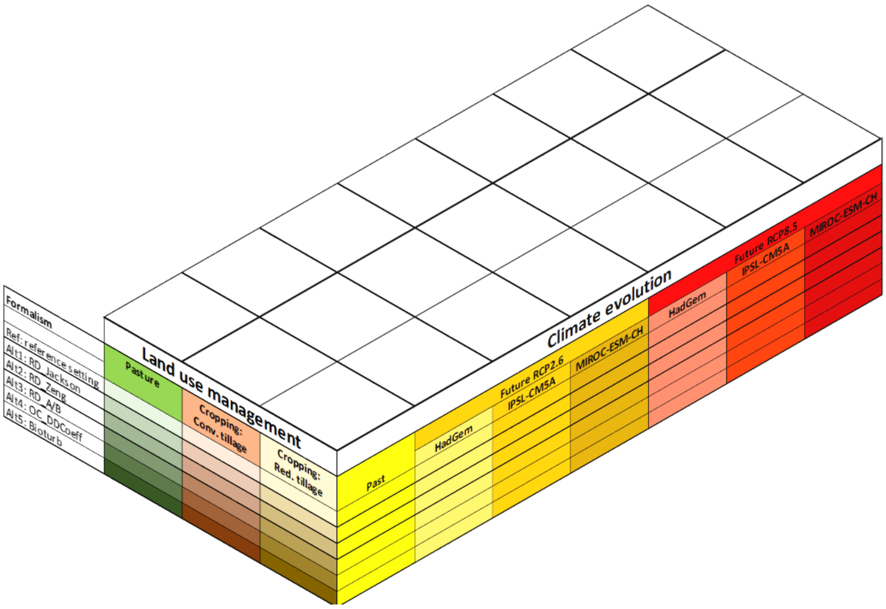


Figure 4: General layout of the simulations.

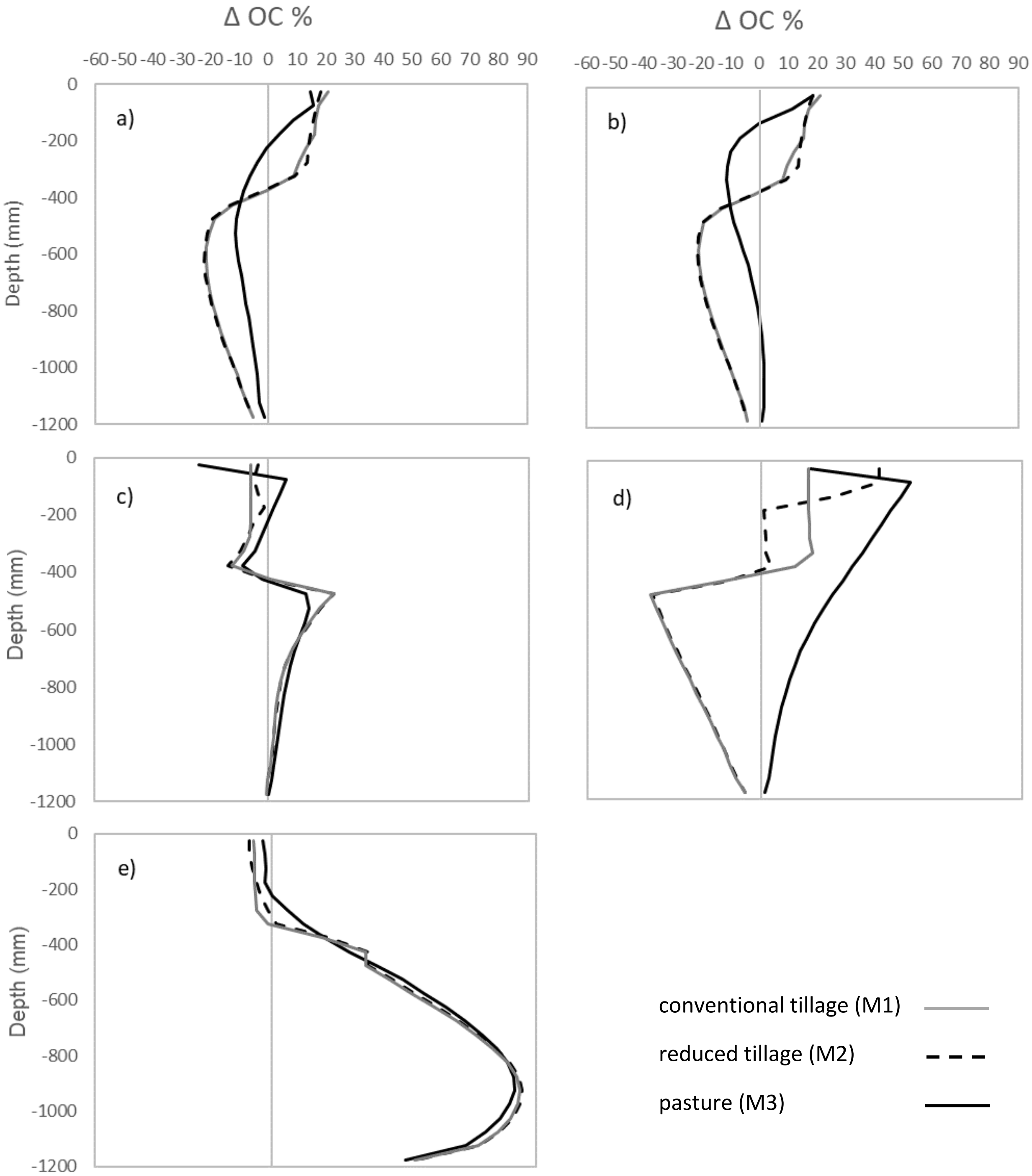
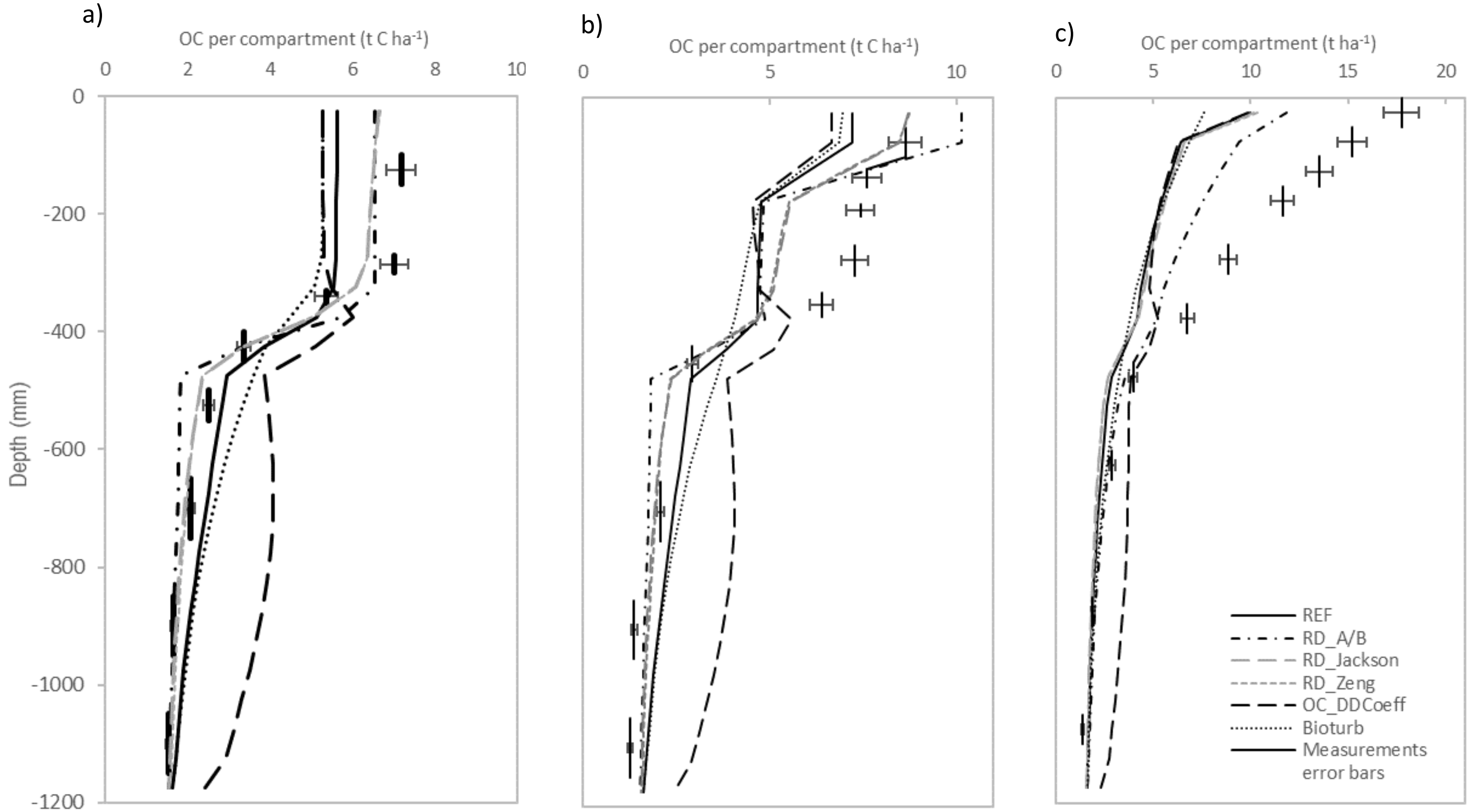


Figure 5: Differences of simulated OC depth distribution between the reference model and the alternative formalisms/parameters for conventional tillage (M1), reduced tillage (M2) and pasture (M3): a) Jackson et al. (1996) rooting density function, b) Zeng. (2001) rooting density function, c) bioturbation, d) above/below ground fresh organic input, and e) depth dependent decomposition rate coefficient.



a)

Figure 6: Simulated OC depth distribution in 2011 by the 6 different versions of OC-VGEN model based different formalisms/parameters and measurements for a) the conventional tillage (M1), b) the reduced tillage (M2), and c) the pasture (M3) profiles. Segmented line with error bars depict the measurements and the associated uncertainties. For description of formalism scenarios see Table 2. Units are t C ha^{-1} per 5 cm-thick layer.

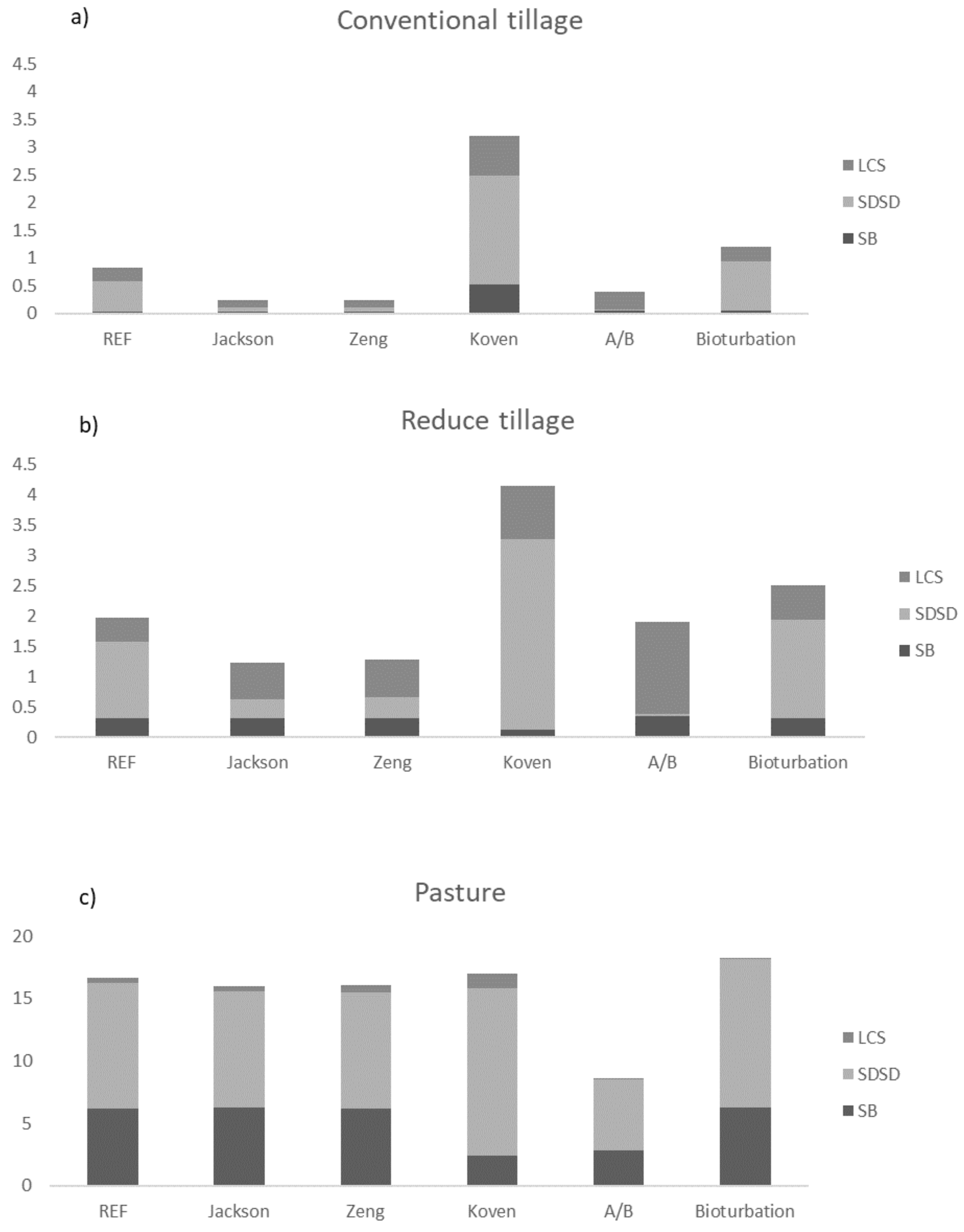


Figure 7: Mean square deviation (MSD) and its components, namely square bias (SB), squared difference between standard deviations (SDSD) and lack of correlation weighted by the standard deviation (LCS) for the OC depth distributions simulated by the 6 model versions compared to measurements for a) conventional tillage (M1), b) reduced tillage (M2) and c) pasture (M3).

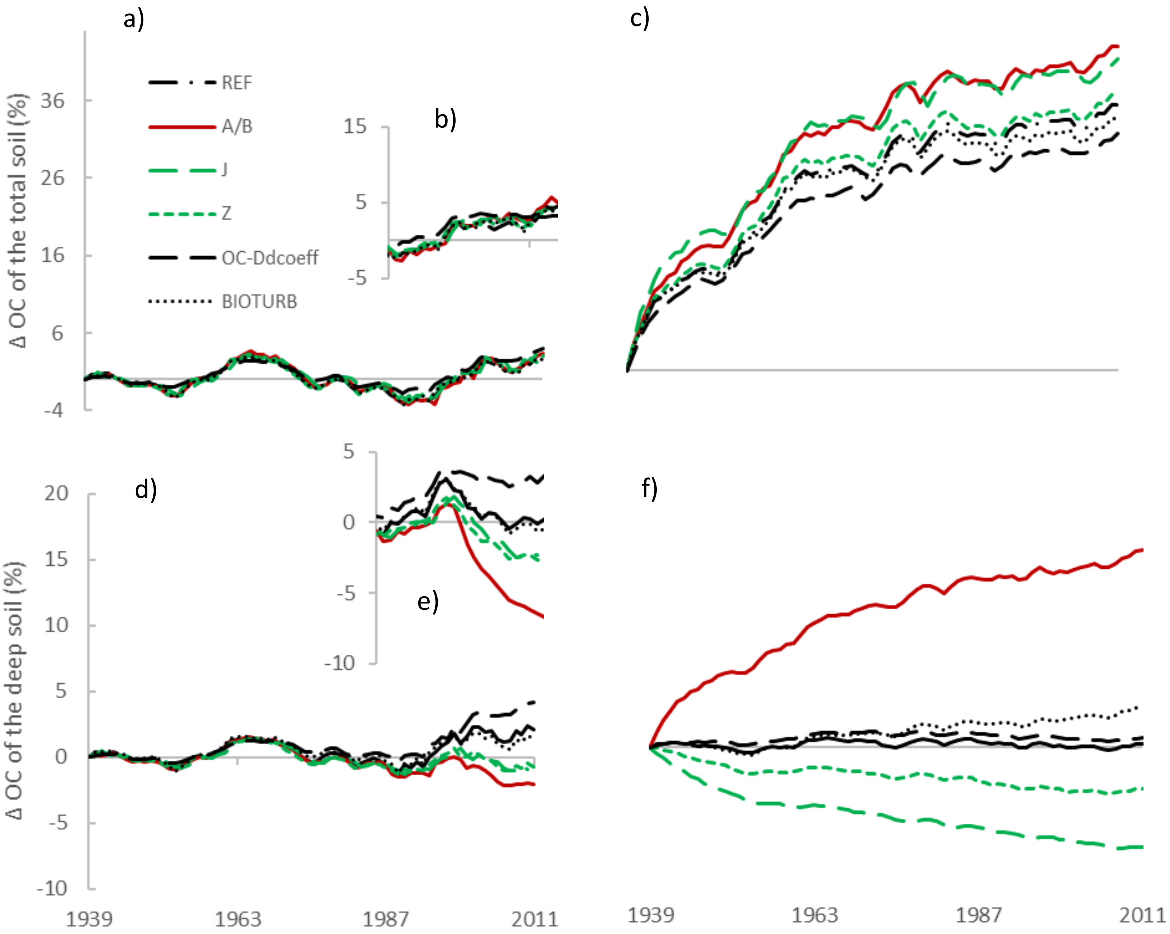


Figure 8: Simulated soil OC stock change relative to the initial stock over 72 years, considering 6 soil process formalisms and parameters. a) and d) represent continuous conventional tillage (M1); b) and e) reduced tillage (M2) and c) and f) pasture (M3). Change in the total OC stock is shown in a), b) and c) and in stock below 30 cm in d), e) and f). For description of the formalisms see Table 2.

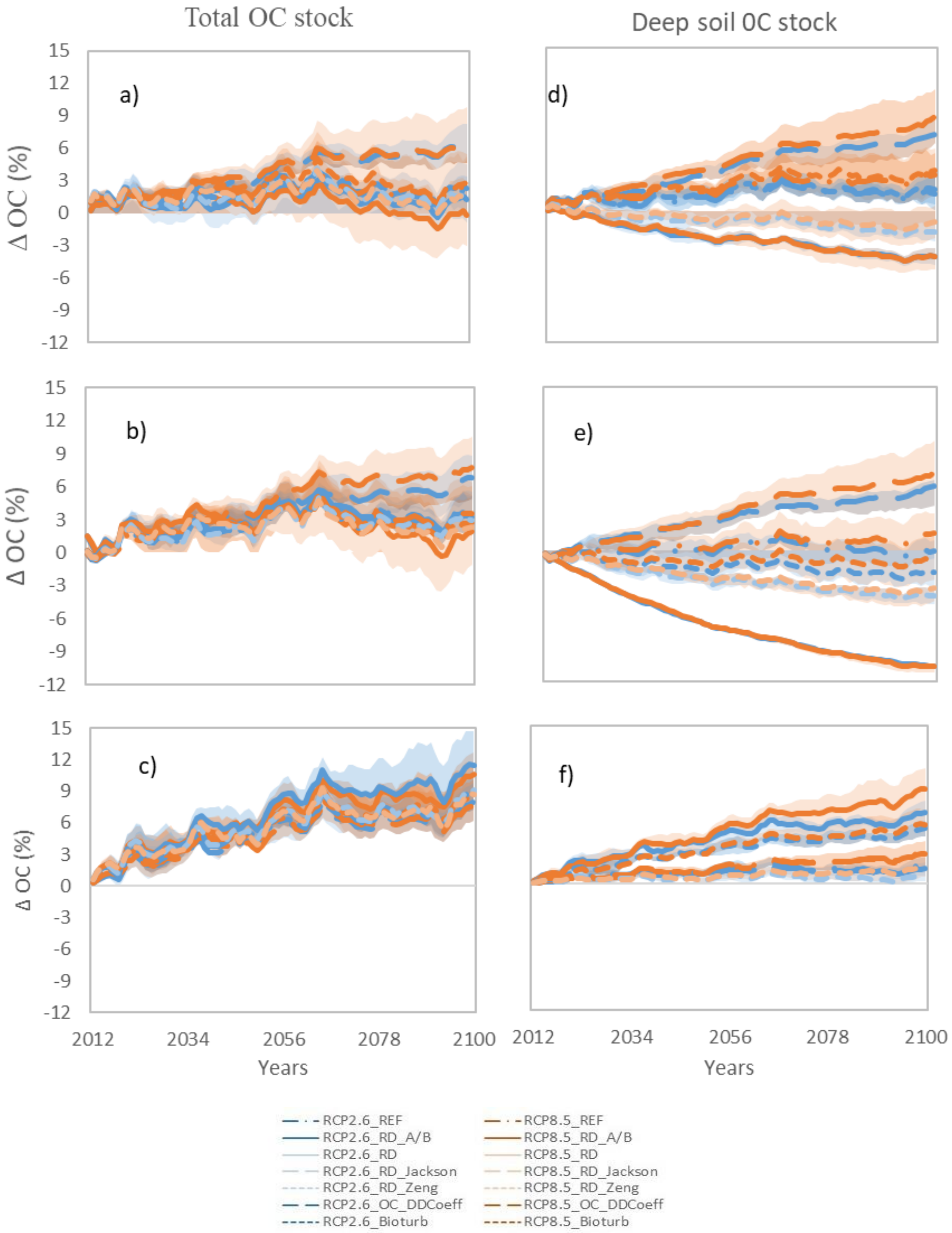


Figure 9: Projection of the total soil OC stock over the coming century considering 6 climatic scenarios and 7 OC-VGEN versions differing by their formalism/parameter. a) and d) represent conventional tillage (M1), b) and e) reduced tillage (M2) and c) and f) pasture (M3). Blue lines represent the RCP2.6 IPCC climatic scenario and red lines represent the RCP8.5 IPCC climatic scenario for all the three Earth System Models. For description of the formalisms, see Table 2. Lines represents the average of the three climatic model for each climatic scenario and the coloured areas represent the bandwidths of the simulation results of the three climatic model for a given climatic scenario.