



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

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

3

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15

16

## 17    **Abstract**

18           Soil organic carbon (OC) sequestration (i.e. the capture and long-term storage of  
19   atmospheric CO<sub>2</sub>) is being considered as a possible solution to mitigate climate change,  
20   notably through land use change (conversion of cropped land into pasture) and  
21   conservation agricultural practices (reduced tillage). Subsoil horizons (from 30 cm to 1  
22   meter) contribute to ca. half the total amount of soil OC, and the slow dynamics of deep OC  
23   as well as the relationships between the OC depth distribution and changes in land use and  
24   tillage practices still need to be modelled.

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

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

40

## 41    **Keywords**

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

## 43 1. Introduction

44 Soil organic matter is the largest terrestrial carbon reservoir that is in constant  
45 exchange with the atmosphere and, consequently, a small change in this carbon reservoir  
46 can have a strong effect on atmospheric CO<sub>2</sub>. Estimating the response of soil organic  
47 carbon (OC) to climate change is crucial (Smith et al., 2008; Minasny et al., 2017) because  
48 soil OC sequestration is being considered as a possible solution to mitigate climate change,  
49 converting atmospheric CO<sub>2</sub> into long-life soil organic carbon. Land use change  
50 (conversion of cropped land into pasture) and conservation agricultural practices  
51 (reduced tillage), considered as a strategy to sequester carbon in soil, have been  
52 extensively studied (Paustian et al., 1997; Jobbágy and Jackson, 2000; Post & Kwon, 2000;  
53 Lal, 2004). Nevertheless, the relationship between the OC depth distribution and changes  
54 in land use and tillage practices is still poorly understood (Jobbágy and Jackson, 2000;  
55 Lorenz and Lal, 2005) and controversial results have been reported concerning the effects  
56 of tillage reduction (Haddaway et al., 2016).

57 Thus, there is an urgent need to better predict the OC stock evolution under land use,  
58 management and climate change scenarios by the year 2100. Heretofore, most predictive  
59 modelling efforts (Smith et al., 2005; Xu et al., 2011; Lugato et al., 2014; Wiesmeier et al.,  
60 2016) concentrated on the upper 30 cm of soil, e.g. those based on RothC (Coleman et al.,  
61 1997) or Century (Parton, 1996). These models describe OC as an ensemble of organic  
62 pools with different decay dynamics, but do not consider other soil processes or depth  
63 distributions. However, while the upper 30 cm (topsoil - A Horizon) of soil profile  
64 represents the highest organic matter concentrations, recent studies show that subsoil  
65 horizons (from 30 cm to 1 meter) contribute to 30 to 63 % of the total amount of soil OC  
66 (Batjes, 2014). Consequently, OC stock prediction must not be restricted to the upper 30  
67 cm of the soil but should also consider deep OC stocks. Indeed, Balesdent et al. (2018)  
68 indicated that "using multilayer soil modules in global carbon models could help to  
69 improve our understanding of soil-atmosphere carbon exchange".

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

83 The processes responsible for deep OC stock change are transport of dissolved OC,  
84 bioturbation, root input and decomposition. Several attempts were made to introduce  
85 these processes in OC dynamic modelling. (e.g., Hilinski, 2001; Braakhekke et al., 2011;  
86 Koven et al., 2013; Riley et al., 2014; Camino-Serrano et al., 2018). Nevertheless, for these  
87 key processes, several numerical representations (including the equations and  
88 parametrization) exist in the literature (e.g. Elzein and Balesdent, 1995; Jackson et al.,  
89 1996; Zeng, 2001; Koven et al., 2013 among others), and are often model-specific. The  
90 impact of these different numerical representations on the simulated OC depth-  
91 distribution should be evaluated. But because of model-specific formalisms, it is difficult to  
92 modify their parameterization because of their imbrication with the parameters of other  
93 processes.

94 In addition, at the century scale, when considering climate change 1) explicit transfer of  
95 water and heat should be considered and 2) inherent soil properties that are important for  
96 OC dynamic, as soil texture, bulk density and hydraulic properties, cannot be considered

97 constant (e.g. Montagne et al., 2008; Boizard et al., 2013). As an example, soil OC content is  
98 related to the soil bulk density, which influences soil hydraulic properties and thus soil  
99 water content that in turn affect the OC decomposition. Because deep OC might be  
100 thousands years old and interacts dynamically with soil development, OC dynamics must  
101 be coupled with a model of pedogenesis. Therefore, the retroaction among soil properties  
102 much be taken into account explicitly.

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

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

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

123 practices (conventional and reduced) and was forced by projection scenarios of climate  
124 and land use at the horizon of 2100.

125

## 126 2. Materials and Methods

### 127 2.1 Description of OC-VGEN model and its variations

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

134

#### 135 2.1.1 The VSoil platform

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

150 To build a model, a set of processes is selected, each process being associated to a module.

151 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

178 obtained by the corresponding version of the model. Climatic condition for these runs are  
179 reported in Figure 2.

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

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

187

### 188 2.1.3. Description of the OC-VGEN modules

#### 189 2.1.3.1 The OC dynamic module

190 The OC dynamic module was developed based on the Rothc-26.3 model (Coleman et al.,  
191 1997) with some adaptation based on SoilGen (Finke and Hutson, 2008). In this model,  
192 fresh organic matter input is split between different pools (decomposable plant material  
193 (DPM), resistant plant material (RPM), biomass (BIO), humus (HUM), inert organic matter  
194 (IOM), Figure 1). Organic matter decomposes over time with half-life that differs strongly  
195 among pools (a month for DPM; one to three years for BIO, three to ten years for RPM,  
196 over 50 years for HUM, IOM is considered as stable in the model; Janik et al., 2002).  
197 Decomposition rates additionally depend on moisture deficit, temperature, soil cover and  
198 texture (Equation 1).

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

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

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

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

207 where  $z_\tau$  is the e-folding depth of the intrinsic decomposition rates. This depth was  
 208 optimized by Koven et al. (2013) to 40 cm.

209 Temperature, moisture deficit and  $< 2 \mu\text{m}$  fraction are also depth dependent and are  
 210 calculated using the same equations from the RothC26.3 model (Jenkinson and Coleman,  
 211 2008)

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

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

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

223

#### 224 2.1.3.2. Water, heat and gas transfer modules

225 OC-VGEN uses Richard's equation to simulate the flow of water and advection-diffusion  
 226 equations to model flow of heat and gas. A central-difference Crank-Nicholson approach is

227 used to solve transport equations. It was developed after Pastis (Cannavo et al., 2006).  
228 Upper boundary conditions in water module allow for surface infiltration, evaporation and  
229 zero flux, while the lower boundary accounts only for free drainage in this study. When the  
230 soil infiltrability is exceeded, a water runoff module simply returns a soil surface potential  
231 to zero. Additionally, the soil cover fraction limits the evaporative flux at the upper  
232 boundary. This fraction is a function of the vegetation.

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

238

#### 239 2.1.3.3. Plant development modules

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

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

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

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

$$RDF(z) = \alpha \cdot e^{-\alpha z} \quad (3)$$

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

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

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

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

268 On the other hand, Jackson et al. (1996) fitted the function developed by Gale and Grigal  
 269 (1987) to a global data set of root profile measurements and reached a global average  
 270 rooting distribution function (Equation 5) that is common for the different plant groups  
 271 (grass, shrubs, crop, trees).

$$RDF(z) = -\ln(\beta) \cdot \beta^z \quad (5)$$

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

275 Zeng (2001) fitted a double exponential equation (Equation 6) on the rooting depths  
 276 reported by Canadell et al. (1996). This equation is an improved version of Jackson et al.  
 277 (1996).

$$RDF(z) = \frac{1}{2}(a \cdot e^{-az} + b \cdot e^{-bz}) \quad (6)$$

278 with  $a$  equals 10.74 and 5.558 m<sup>-1</sup>, and  $b$ , 2.608 and 2.614 m<sup>-1</sup>, for pasture and crop  
 279 respectively.

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

288 Lastly, root water uptake calculation, a sink term in Richard's equation, is based on  
 289 LEACHC (Hutson, 2003). This function optimizes the root water potential to minimize the  
 290 difference between the transpiration demand and the flux of water from the soil to the  
 291 roots taking into account the fraction of active roots present, the soil-water matrix  
 292 potential (m) and hydraulic conductivity (m s<sup>-1</sup>) at each soil layer. The transpiration  
 293 demand is calculated from the potential evapotranspiration and the vegetation  
 294 development provided by the crop development module.

295

#### 296 2.1.3.4 Mass mixing modules

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

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

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

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

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

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

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

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

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

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

327

#### 328 2.1.3.5. The mass balance process

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

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

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

337

#### 338 2.1.4. OC-VGEN input data requirements, time step and depth discretization

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



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

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

350

## 351 2.2 Evaluation data set, forcings and statistical analyses

### 352 2.2.1. Evaluation data set

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

360

### 361 2.2.2. Forcing data set

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

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

365 For the 1939-2011 period, forcing data consisted in the land use history of the three above  
366 described plots. OC inputs are known for the last 10 years for the two-cropped plots and  
367 estimated at 5 until 1970 and then at 4 t ha<sup>-1</sup> yr<sup>-1</sup> from 1970 to 2001 (Figure 2c). This  
368 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<sup>-1</sup> yr<sup>-1</sup> 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<sup>-1</sup>) 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,  $\Delta OC$ , calculated in Equation 10.

$$\Delta OC = 100 \times \frac{OC_{Alt} - OC_{Ref}}{OC_{Ref}} \quad (10)$$

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

394 to be in the soil profile. We specifically looked into deep OC stocks response to different  
 395 formalisms or parameters. Below 30 cm, OC stocks are considered as deep OC in this  
 396 study.

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

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

$$405 \quad MSD = \frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2 = (\bar{x} - \bar{y})^2 + \frac{1}{n} \sum_{i=1}^n [(x_i - \bar{x}) - (y_i - \bar{y})]^2 \quad (11)$$

$$406 \quad SB = (\bar{x} - \bar{y})^2 \quad (12)$$

$$407 \quad SDSD = (SD_s - SD_m)^2 \quad (13)$$

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

409 And finally,

$$410 \quad LSC = 2SD_s SD_m (1 - r) \quad (14)$$

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

$$413 \quad r = \frac{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{SD_s SD_m} \quad (15)$$

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



### 417 3. Results and discussion

#### 418 3.1 Impact of formalism of key OC depth distribution processes

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

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

442 ***The use of conventional diffusive transport of OC for bioturbation*** instead of a vertical  
443 mixing of matter (based on SoilGen2.24, Finke, 2012) increased the OC stocks between 45

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

450 ***Effect of the above/below ground ratio of fresh organic carbon input*** - For pasture, the  
451 alternative scenario corresponded to an increase of the below ground contribution while  
452 for agriculture it corresponded to a decrease. In the case of pasture, increasing the below  
453 ground contribution logically increased the OC stocks over the whole soil profile by 15 to  
454 50 % depending on the considered depth (Figure 5d), with a maximum increase round 10  
455 cm. The total soil OC stocks increased by 23% while the ectorganic layer decreased by  
456 60% (Table 4). For agriculture, reducing the below ground input did not affect the total  
457 soil OC stock (Table 4) since both above and below ground inputs are mixed by tillage.  
458 However, it increased the OC input to the soil in the tillage layer and conversely decreased  
459 the soil OC input by roots. Therefore, a decrease of the OC stock below 40 cm was  
460 observed. This decrease was maximal around 50 cm, where the root proportion was still  
461 important, and it became lower below that depth as the root abundance decreased. Above  
462 40 cm, the OC stocks increased by 15 % on the entire depth interval for the conventional  
463 tillage and by 40 % over the 10 upper centimetres for the reduced tillage plot (Figure 5d).

464 ***The introduction of a depth-variable decomposition rate coefficient*** only influenced the  
465 OC depth distribution below 30 cm since the decomposition rate coefficients used above  
466 that depth were the same in the reference and OC\_DDCoeff models. The exponential  
467 decrease with depth of the decomposition rate coefficient increased as expected the OC  
468 stocks up to 85 % at around 100 cm depth for all the considered land uses and tillage  
469 practices (Figure 5e). Below the bioturbation depth (i.e., 50 cm), models that combine an  
470 exponential decrease with depth of both root input ( $\exp(-\alpha z)$ , Eq.3) and decay rates ( $\exp(-\zeta z)$ ,

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

498 the small LSC values. At last, increasing the belowground contribution of fresh litter  
499 provided the best estimation of the OC stock measurements in the pasture (Figure 7c). The  
500 strong difference in the model ability to reproduce the OC total stock between cultivation  
501 and pasture can be explained by the parametrization of the RothC module that was the  
502 same for the two land uses and better suited for cultivation.

503

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

540

### 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

553 and the alternative root density function models decreased those stocks by 3.5 % and  
554 2.5 % respectively. The depth dependent decomposition rate coefficient simulated a 2.6 %  
555 increase of deep OC stocks compared to the reference model. These evolutions are in  
556 agreement with the results discussed in the previous section. The depth dependent  
557 decomposition rate coefficient increased the OC depth accumulation and thus  
558 counteracted the effect of the shallower ploughing on the OC input to the soil. On the  
559 opposite, the decrease of the above/belowground ratio of fresh organic matter and the  
560 change of root ground formalisms decreased the deep OC stocks.

561 For 10 years of reduced tillage (from year 2000), no differences with the conventional  
562 tillage were simulated for the total OC stocks (Figure 8b), while, when considering only  
563 deep OC, the deviation among different models became more pronounced. The deep OC  
564 stocks simulated by the model with depth dependent decomposition rate coefficient  
565 followed more or less the same trend as the total OC stocks, while, for all the other  
566 simulations, the deep OC stocks decreased from years after 2000. This decrease reached  
567 3 % by the year 2011 for the reference and diffusive bioturbation models, 5 % for the  
568 alternative root growth formalisms and up to 10 % for the increased above/below ground  
569 input model (Figure 8e). These results showed that a further shallowing of the ploughing  
570 depth increased the trends observed after the year 2000 in the case of the agriculture with  
571 conventional tillage. Reduced tillage did not increase the total OC stock compared to  
572 conventional tillage. While considering the upper 30 cm, a slight increase ranging from 0  
573 to 9 % was observed. Most experiments on reduced tillage in the literature were  
574 conducted on durations ranging from 0 to 15 years and thus comparable to the  
575 experiment considered in this study. Recent meta-analysis (Baker et al., 2007; Bai et al.,  
576 2018) described no significant change in total OC stock with reduced tillage but a change  
577 in soil OC distribution comparable to that obtained in this study. Dimassi et al. (2014)  
578 attributed this difference to differences in soil climate (water content notably) due to the  
579 tillage practices. Our modelling approach could not reproduce such a difference in soil

580 climate due to tillage reduction; the observed changes in OC stocks were mainly due to  
581 change in mixing depth and intensity.

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

### 595 3.2.2 Impact of two climate change scenarios by the years 2100 on the soil OC storage 596 simulations for three different land use and agricultural practice modalities

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

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

606 For deep OC stocks (30-120cm), the situation was once again more complex. The increase  
607 of above/below ground ratio of fresh organic input led to a decrease of the deep OC  
608 stock by 4 and 11 % for conventional and reduced tillage respectively, as well as the use of  
609 an alternative root density function (Zeng, 2001) although to a lesser extent (3 % for both  
610 plots). In contrast, the model with depth dependent decomposition rate coefficients  
611 increased the deep OC stock to a maximum of 8 % for both cropped plots. The reference  
612 model and diffusive bioturbation did not induce a significant change over the simulated  
613 period. On cropped profiles, the variations of deep OC stocks related to the formalisms/  
614 parameters used in the model were larger than that of total OC stocks (Figures 9d and e)  
615 and were more marked for shallower tillage, while the effect of IPCC scenarios stayed in  
616 the range of 3 %. For pasture, most of the simulations predicted an increase in deep OC  
617 stocks, with the exception of the simulation with Jackson et al. (1996)'s root density  
618 function that resulted in a slight decrease of the deep OC stock. The maximum increases of  
619 6 to 9 % for PRC2.6 and RPC8.5 respectively were simulated by the model with higher  
620 below ground fresh organic input (Figure 9f). The effect of IPCC scenarios again produced  
621 changes in the deep OC stocks ranging from 0 to 3 %.

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

628 Other studies projecting OC stocks over the 21<sup>st</sup> century only considered the upper 30 cm  
629 of the soil (e.g., Smith et al., 2005; Lugato et al., 2014; Wiesmeier et al., 2016). In this study,  
630 by introducing new soil processes and the uncertainty related to their knowledge, we  
631 showed that the simulated behaviour of deep OC differs substantially from that of top soil  
632 OC stocks. We showed that while for the total OC stocks (as well as top 30 cm OC stocks)

633 an increase could be projected considering the suggested climate change scenarios; both  
634 an increase and a decrease in deep OC stock are possible over the coming century  
635 depending on the formalism/parameter considered in the simulation.

636

## 637   **Conclusion**

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

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

661   We proposed here a first modelling approach for OC stock estimation considering most  
662   soil processes and their feedbacks. Our study demonstrated that, due to a limited  
663   knowledge, considering soil processes added a lot of uncertainties on the soil OC stock

664 projections, notably for the deep soil OC, and thus more effort should be done in  
665 evaluating the most reasonable combination of formalisms for soil processes and their  
666 parametrization. To do so, this work should be extended to different soil types under  
667 different climates in which the hierarchy of the processes could be different, thus allowing  
668 better conclusions on the formalisms to be chosen for the different soil processes. Future  
669 research with models such as OC-VGEN should especially focus on the above to below  
670 ground fresh organic input ratio and on depth-dependent OC decomposition rate  
671 coefficients, since OC-VGEN is the most sensitive to these formalisms/parameters.  
672 Combining modelling and isotopic tracing approaches, by introducing the isotopes in the  
673 models could allow overcoming this limit.

674

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## 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.

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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<sup>-1</sup> 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<sup>-1</sup>) simulated at the end of the 72 years simulations with different soil processes formalisms/parameters in OC-VGEN for the three experimental plots.

**Table**

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<b>Process</b>		<b>Module</b>	<b>Original model</b>	<b>Reference</b>
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)
<b>Solid mineral balance</b>		<b>Balancing soil characteristics</b>	<b>OC-VGEN</b>	<b>This study</b>

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	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)$
	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	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)$
	Pasture		58/42		
Alt 2 - RD_Zeng	Crop	$RDF(z) = \frac{1}{2} (\alpha. e^{-\alpha z} + b. e^{-bz})$	41/59	Mixing model after SoilGen2.24	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)$
	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	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)$
	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	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)r_z(z)$
	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		
	Pasture	$RDF(z) = \alpha. e^{-\alpha z}$	58/42	$\frac{\partial M_{oc}(z, t)}{\partial t} = D(z) \frac{\partial^2 M_{oc}(z, t)}{\partial z^2}$	$K(z) = K_{0,p}T_T(z)r_{w\tau}(z)r_{sc}(z)$

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

<b>Site</b>		<b>Mons</b>
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<sup>-1</sup>) 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 conventional tillage (M1)	reduced tillage (M2)	Pasture (M3)
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

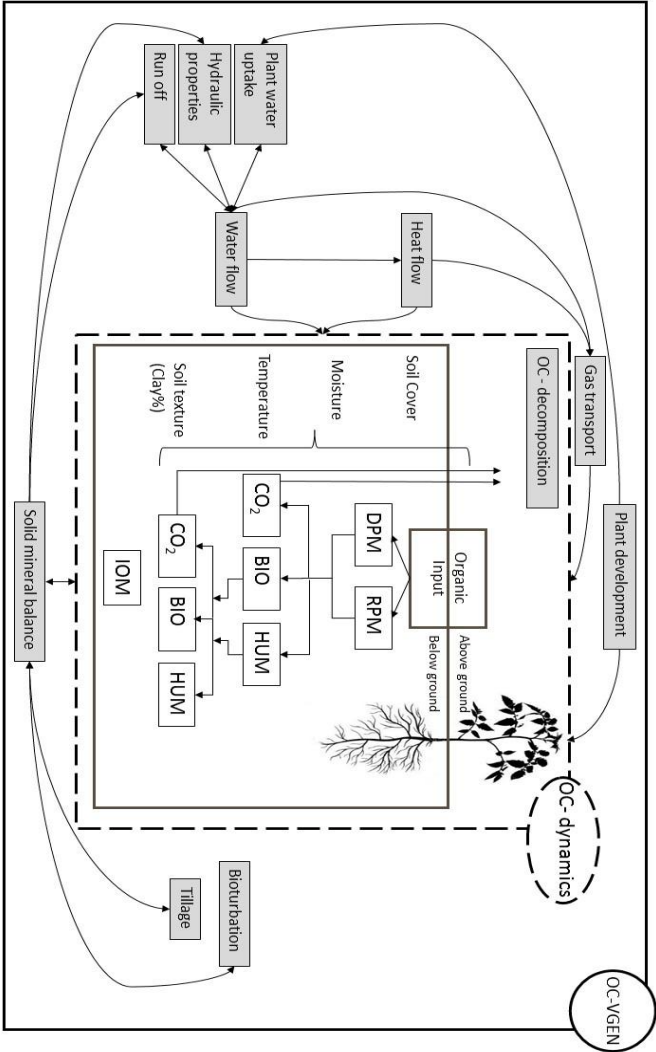


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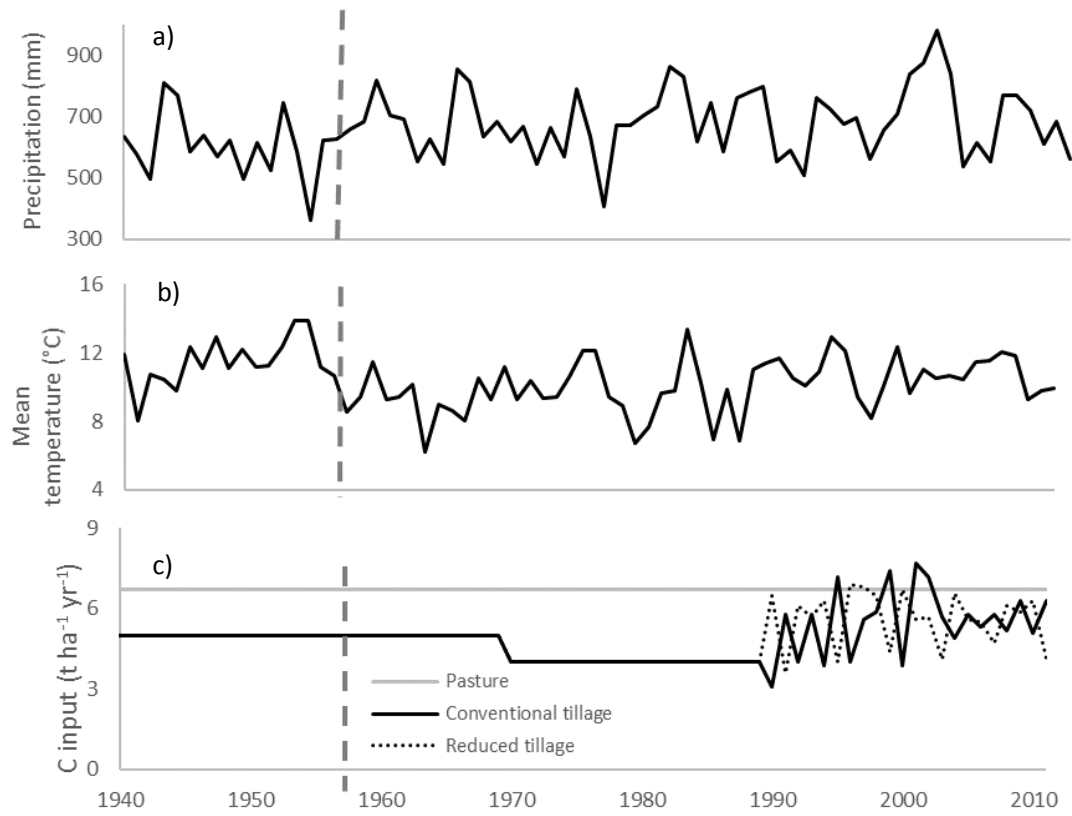


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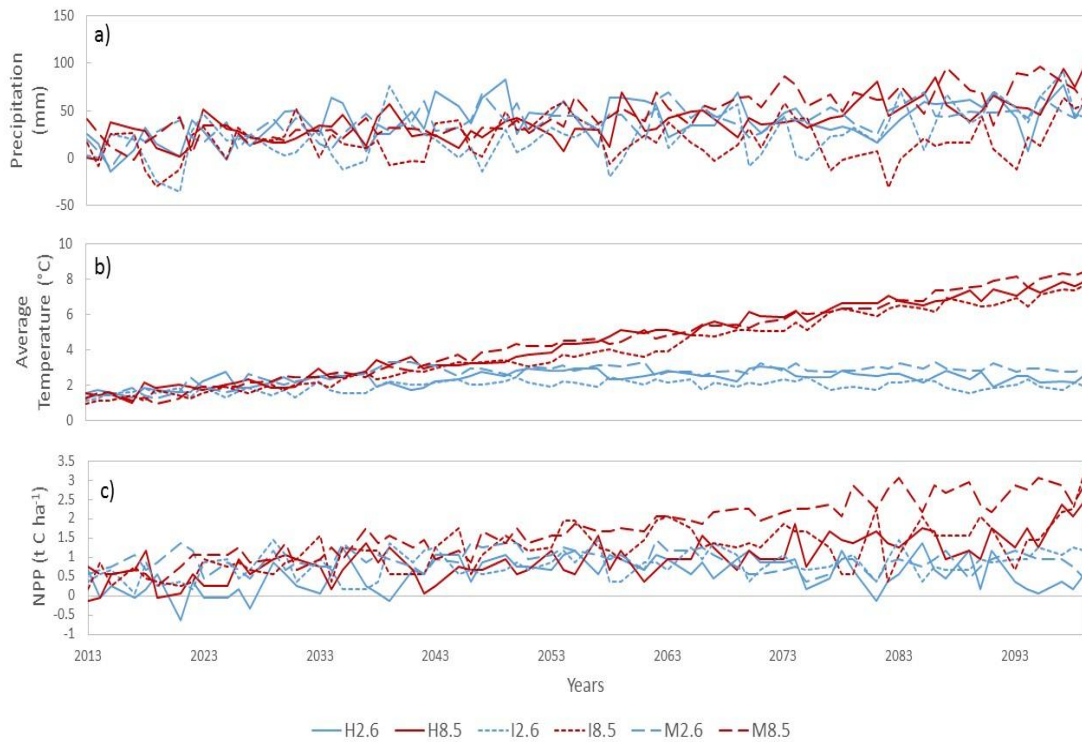


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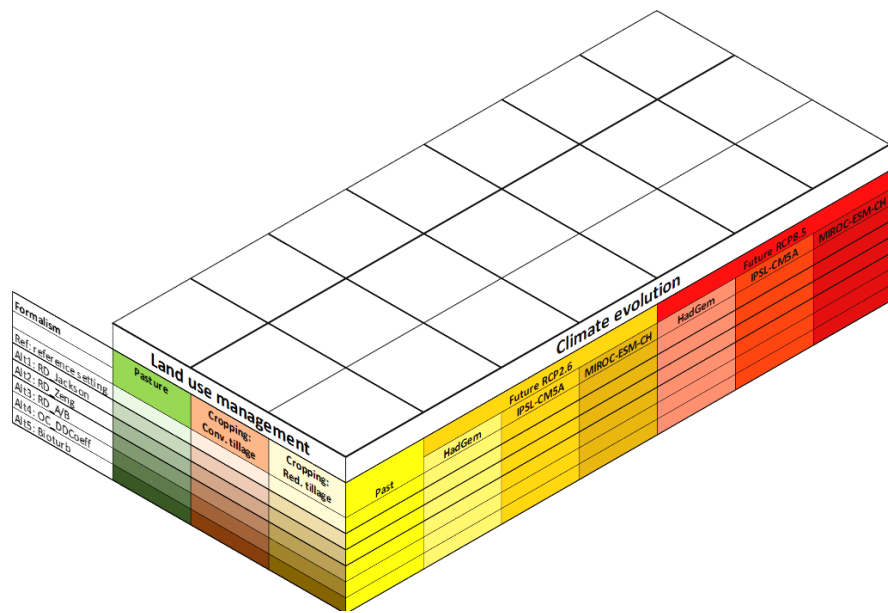


Figure 4: General layout of the simulations.

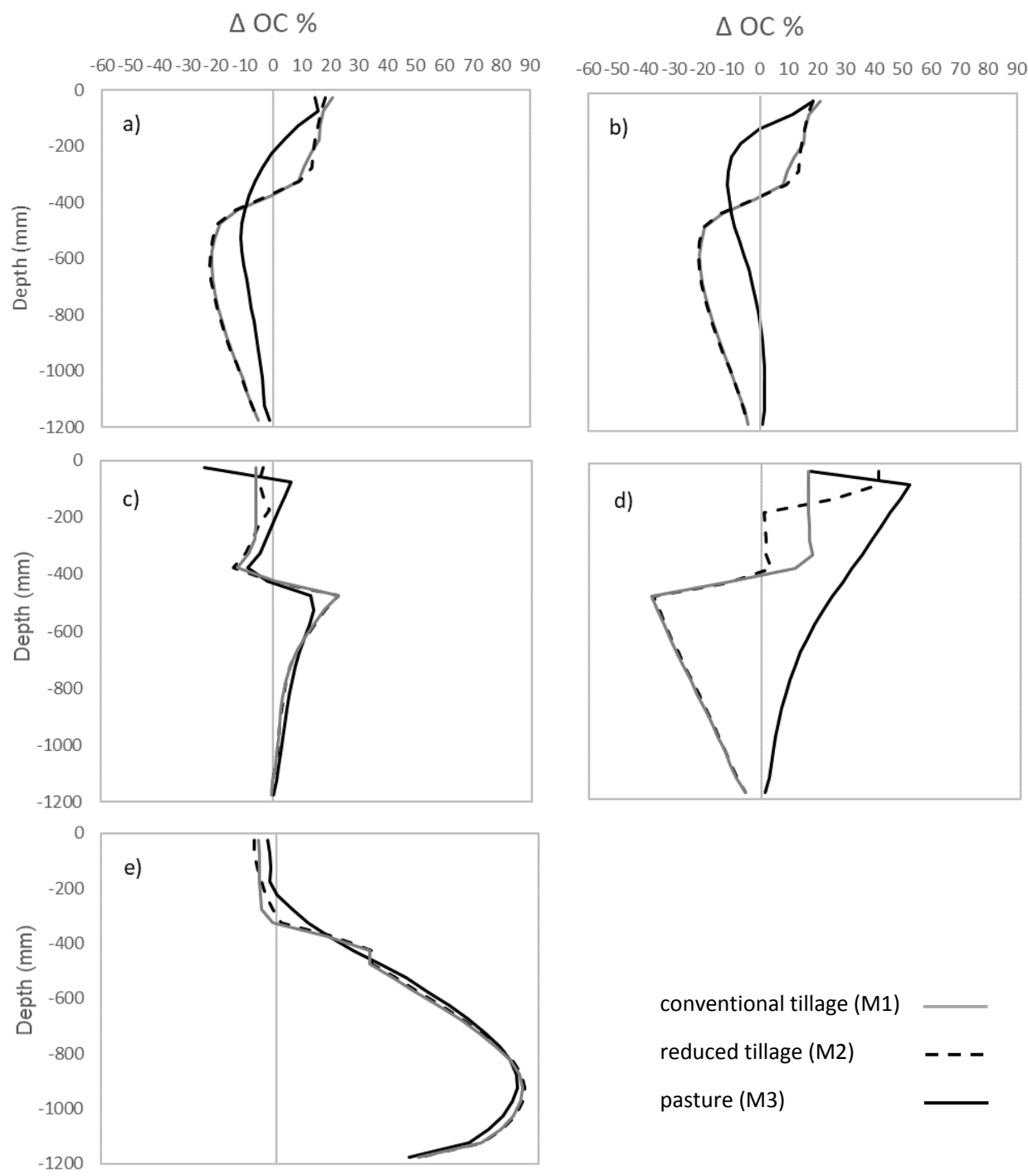


Figure 5: Differences of simulated OC depth distribution between the reference model and the alternative formalisms/parameters for conventional tillage (M1), reduced tillage (M2) and pasture (M3): a) Jackson et al. (1996) rooting density function, b) Zeng. (2001) rooting density function, c) bioturbation,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

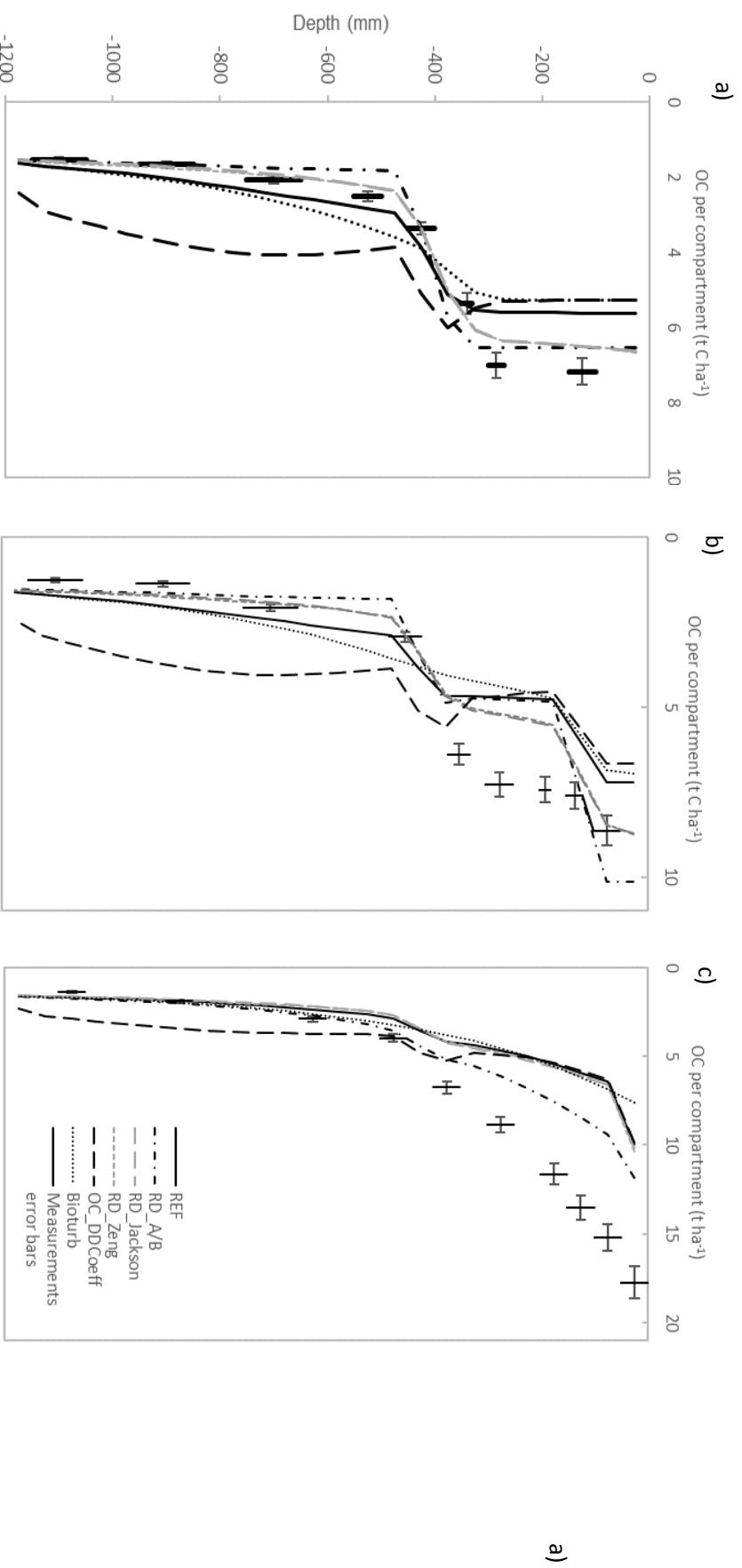


Figure 6: Simulated OC depth distribution in 2011 by the 6 different versions of OC-VGEN model based different formalisms/parameters and measurements for a) the conventional tillage (M1), b) the reduced tillage (M2), and c) the pasture (M3) profiles. Segmented line with error bars depict the measurements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

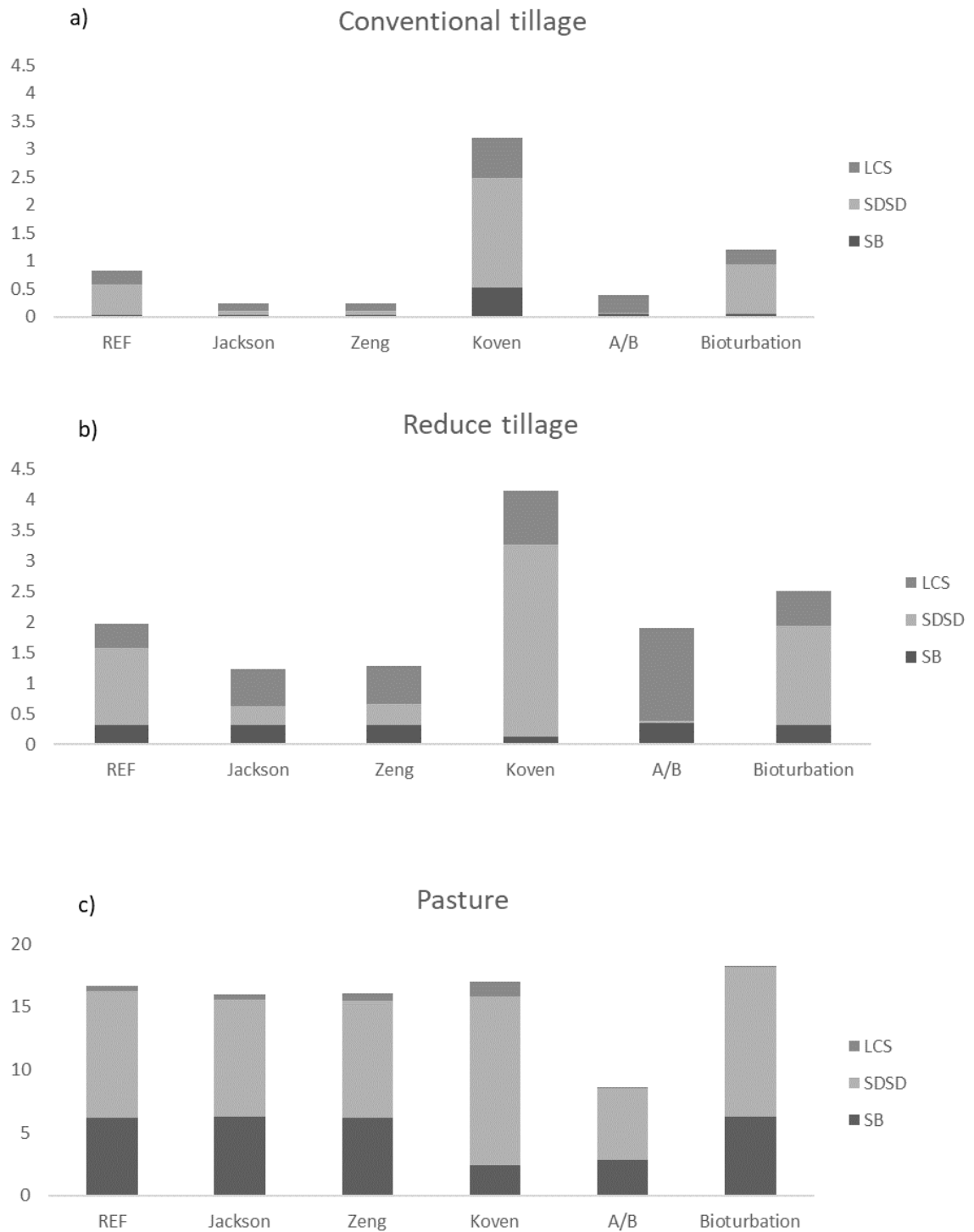


Figure 7: Mean square deviation (MSD) and its components, namely square bias (SB), squared difference between standard deviations (SDSD) and lack of correlation weighted by the standard deviation (LCS) for the OC depth distributions simulated by the 6 model versions compared to measurements for a) conventional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



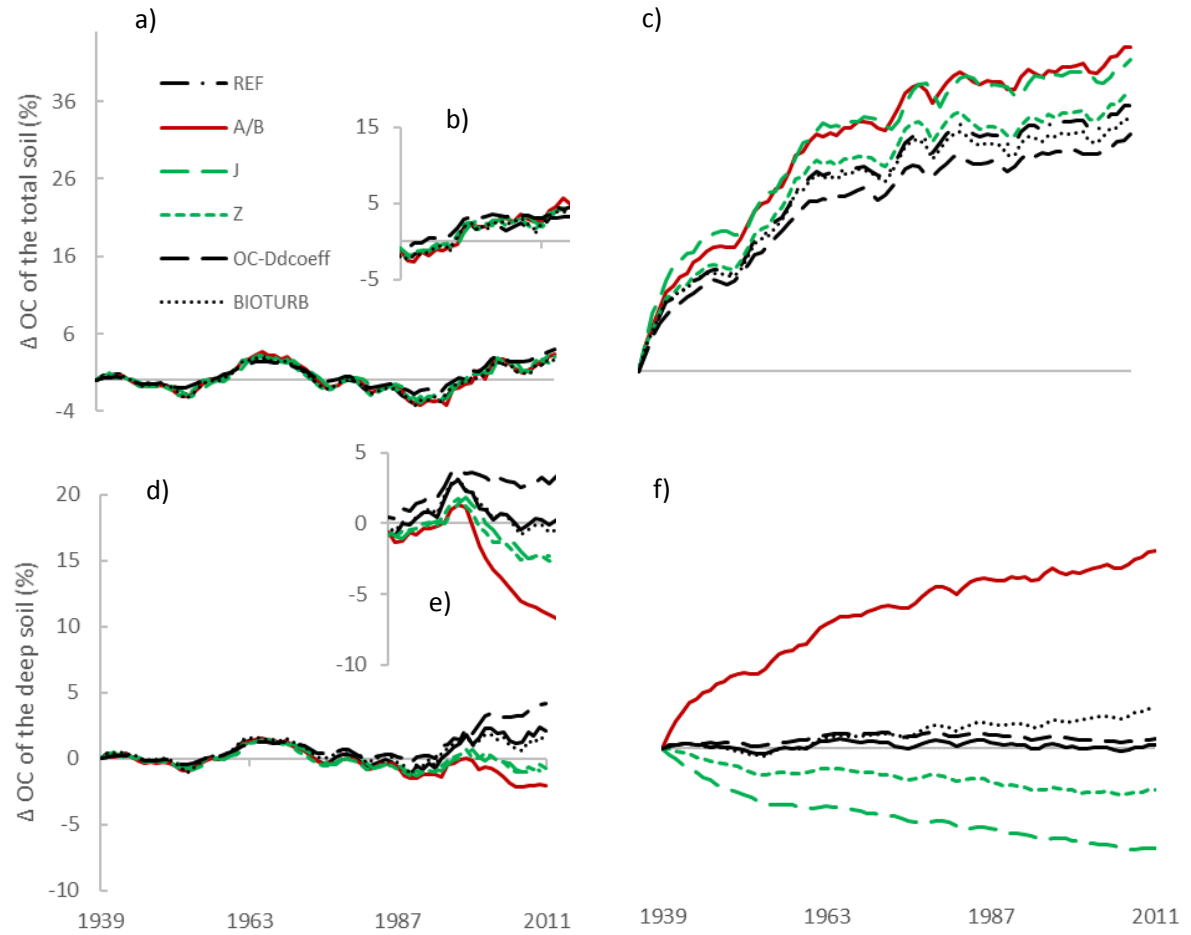


Figure 8: Simulated soil OC stock change relative to the initial stock over 72 years, considering 6 soil process formalisms and parameters. a) and d) represent continuous conventional tillage (M1); b) and e) reduced tillage (M2) and c) and f) pasture (M3). Change in the total OC stock is shown in a),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

# Figure

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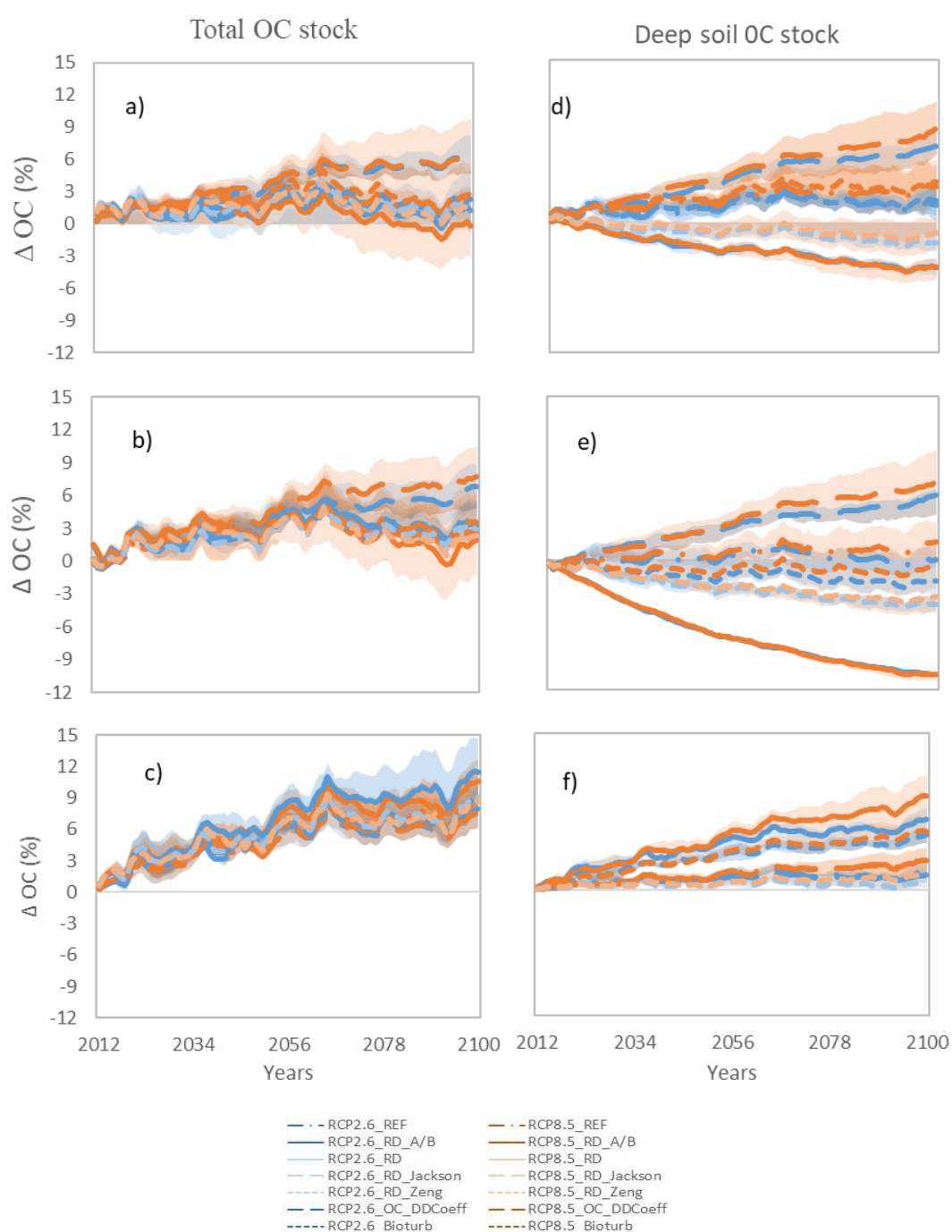


Figure 9: Projection of the total soil OC stock over the coming century considering 6 climatic scenarios and 7 OC-VGEN versions differing by their formalism/parameter. a) and d) represent conventional tillage (M1), b) and e) reduced tillage (M2) and c) and f) pasture (M3). Blue lines represent the RCP2.6 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.