

Modelling the dynamics of soil macroporosity

Abstract

Many factors affect soil porosity but major of them are soil fauna, plant roots and the climate. Many studies attempted to investigate the effect of these factors on the evolution of soil porosity separately. The objective of is this study is, based on an in situ experiment including three major porosity factors, propose a model of soil macroporosity evolution. In situ observation and quantification of the evolution of macroporosity under the influence of each agent separately and the three agents combined allow to propose a model for each case. Mathematical algorithms and computing are necessary to formalise this model and longterm experiment is needed to validate this model.

Keywords: Differential equations, Soil structure, Earthworms, Casts production, Swelling Shrinkage, Plant roots

1. Introduction

2 Soil, due to its importance in furnishing ecosystem services, attracted the
3 attention of many soil scientists for many years. Many processes occurring in
4 soil are defined and characterized but to better understand the fate of impor-
5 tant factors, modelling approach has been developed. Since then, a various
6 models concerning soil processes were developed and a historical point of
7 view of this modelling is given by Vereecken et al. (2016). Among these
8 processes soil structure, defined as the rearrangement of solid soil particles
9 got a great interest. The consequence of this arrangement is the formation

10 of aggregates and voids. Many studies highlight the main factors that in-
11 fluence soil structure and the five major of them are i) soil fauna, ii) plant
12 roots, iii) environmental factors, iv) inorganic binding agents and v) soil mi-
13 croorganisms (Six et al., 2004). Research have been leaded to investigate
14 the role of different agents on the evolution of structure. Plant roots influ-
15 ence soil structure in different ways but the most studied is by introducing
16 organic matter. This process in widely investigated and some models have
17 been proposed. For example, Roth-C study the soil organic matter turnover
18 in non-waterlogged soils (Coleman and Jinkinson, 1999) and how this pro-
19 cess is involved in soil structure (aggregation formation). Based on Roth-C,
20 Malamoud et al. (2009) proposed a new model which studies the dynamics
21 of soil structure (aggregation and porosity) named Structure-C. This model
22 written in Matlab consists of three sub models. An aggregation submodel,
23 organic matter submodel and porosity submodel. The porosity submodel
24 predicts the evolution of porosity during time under specific conditions of
25 soil organic matter turnover.

26 Apart from its action in creating structure by introducing organic matter
27 in soil, plant roots also enmesh soil particles and creates aggregates between
28 what pores are created. This aspect of research is not widely explored. Nev-
29 ertheless, the process is detailed by Jangorzo et al. (2015). A more complex
30 modelling platform has been developed to help understanding and simulate
31 major processes governing soil evolution. This platform named Virtual Soil
32 or Vsoil (Lafolie et al., 2015) is designed to facilitate modelling chemical,
33 physical and biological interactions occurring in soils and improve the simu-
34 lation of anthropic activities and climate change impact on the soil ecosystem
35 services. Different contributors may work together in order to develop mod-
36 ules that can be incorporated in the platform. Since then, module of organic
37 matter turnover, water dynamics are developed. An important module to de-
38 velop will be that which concern the dynamic of soil structure (porosity and
39 aggregation). Such a module exists, example Structure-C developed based
40 on Roth-C. It describes the evolution of soil structure under the influence
41 of soil organic matter dynamics and the agents that condition this evolution
42 (Malamoud et al., 2009). This model does not take into account the fact
43 that soil porosity evolves according to the influence of other major processes
44 like earthworm activities as well as the physical process occurring in soil like
45 swelling and shrinkage. The role of earthworms in soil structure is also widely
46 studied and an attempt to model this process has been undertaken.

47 Another phenomenon that influence soil porosity is the wetting-drying

48 cycle related to property of swelling and cracking of the soil. Many stud-
49 ies have been undertaken to study the process of soil cracking (Konrad and
50 Ayad, 1997; Greco, 2002; Braudeau and Mohtar, 2006; Peng and Horn, 2007;
51 Chertkov, 2012b,a) and its impact on soil porosity (Coppola et al., 2012,
52 2015). In a recent work, Stewart et al. (2016) showed that most of mod-
53 els developed do not consider the process in its whole. However, the total
54 porosity produced during soil cracking in a swelling soil could be apportioned
55 in three parts: aggregates porosity, shrinkage cracks and vertical subsidence
56 and then proposed a unified model. There is an ongoing debate concerning
57 the vertical subsidence as part of soil porosity in a swelling soil. However, we
58 assume that the vertical subsidence is taken into account when considering
59 the decrease of aggregates porosity during soil compaction. Moreover, the
60 model of Stewart did not consider the repeating wetting-drying process or a
61 successive swelling-shrinkage which naturally happened in a Vertisol. This
62 why he assumed that the mass movement and erosion were insignificant.
63 But, in a wetting-drying cycle, mass movement is the major driver of cracks
64 dynamic (Jangorzo et al., 2015). Nevertheless, a part of this model could be
65 integrated in a new model development by considering it as the state of the
66 porosity in the first swelling-shrinkage process.

67 Two mechanisms drive the swelling-shrinkage cycle in soil. Mechanical
68 loading mechanism and the second associated with the change in suction
69 known as hydraulic loading mechanism (Wang and Wei, 2014). Mecha-
70 nism of reversible swelling-shrinkage strain and the Mechanism of irreversible
71 swelling-shrinkage strain (Wang and Wei, 2014) shows the behaviour of soil
72 volume during swelling-shrinkage cycle. This volume is assumed to be irre-
73 versible (Tessier, 1984; Jangorzo et al., 2015) in natural conditions. More the
74 drying is important less the soil uptake water during wetting which means
75 that the soil will swell less (volume decrease) (Croney and Coleman, 1954).
76 Earthworm, considered as ecosystem engineer (Jones et al., 1994) have been
77 widely studied in the context of their role in soil structure. The efficiency
78 of these engineers (activity), particularly earthworms depends on three fac-
79 tors (Kretzschmar, 1991). However, earthworms are more active in a range
80 of water potential, when soil is loose and depending on the period of year.
81 This activity conditioned the effect of this engineer on soil structure as the
82 latter depends on the intensity of burrowing (Jangorzo et al., 2015). Ac-
83 tivity of earthworm is also conditioned by soil temperature and individual
84 mass of the organism (Kaneda et al., 2016). Based on laboratory and field
85 experiments, many models have been developed to predict the role of some

86 earthworm species in soil aggregation (e.g. Kaneda et al., 2016) or in soil
 87 carbon sequestration (e.g. Komarov et al., 2017). But these models neither
 88 they did not predict the evolution of soil porosity nor they did not consider
 89 the synergy that exist between plant roots and earthworm in soil structure
 90 (Zangerlé et al., 2011; Jangorzo et al., 2015). One of the factor that most
 91 incites earthworm burrowing is the food seeking. However, earthworm moves
 92 into different layer of soil to find fresh organic matter that they decompose
 93 and translocate sometimes deeper in the soil (Jangorzo, 2013). We could
 94 then assume that more food is available, greater is the burrowing activity.
 95 This assumption is modelled by Daniel (1991) when he studied the effect of
 96 food consumption on aggregates formation. The degree of soil organic mat-
 97 ter transformation by earthworm is conceptualized and modelled by Chertov
 98 et al. (2017) and Komarov et al. (2017). If the soil aggregate formation is
 99 known, it is not the case for the porosity existing in and between aggre-
 100 gates. The aim of this work is to develop a mathematical integrated model
 101 describing the porosity dynamics in model soils “constructed Technosols”.
 102 This multi-agents model takes into account the effect of three ranked factors
 103 -wetting-drying cycle, plant roots and soil fauna- (Jangorzo et al; 2017, data
 104 not published) in the evolution of soil structure.

105 2. Model theory

106 2.1. General model of soil porosity dynamics

107 We hypothesis that the changes of macroporosity P with time t , $\frac{dP}{dt}$,
 108 depends on the variation of macroporosity due to i) soil moisture $f(\Theta)$, ii)
 109 the population dynamics of roots $f(r)$, and iii) the earthworm activity $f(w)$
 110 respectively, as well as a porosity disappearance term D_P :

$$\frac{dP}{dt} = f(\Theta) + f(r) + f(w) - D_P. \quad (1)$$

111 2.2. Changes in porosity due to variations in soil humidity (wetting and dry- 112 ing cycles)

113 In clayey soils like Vertisols or in Technosols made of swelling materials
 114 like paper or iron industry sludges, there are changes in soil porosity with
 115 the variations of soil humidity (Peng and Horn, 2007; Huot et al., 2014,
 116 BIOTECHNOSOL, others?). This shrinkage and swelling behaviour

117 When a soil is set up and watered, the first process that affects its porosity
 118 is water loss. The behaviour of water movement in soil has been largely stud-
 119 ied, particularly the process of swelling-shrinkage (Smiles, 2000). According
 120 to its texture, soil swells when it is wetted which causes an increase of vol-
 121 ume, a decrease of bulk density, and an increase in macroporosity (Smiles,
 122 2000). Conversely, when the soil dries, it shrinks and its volume decreases
 123 which leads to an increase of soil bulk density (Peng and Horn, 2007), a de-
 124 crease of aggregates porosity (microporosity), and an increase of shrinkage
 125 cracks (macroporosity) (Stewart et al., 2016). But, as the volume of cracks
 126 is important, we assume that the total porosity of the soil increases as soon
 127 as the water potential increases.

128 Stewart et al. (2016) have proposed and validated a unified model to
 129 represent the variations of the different types of porosity with the changes in
 130 soil humidity. They consider three types of porosity:

131 In absence of any other agents, here we assume that the effect of micro-
 132 organisms is negligible, the main process that govern porosity formation is
 133 water flow expressed by the swelling-shrinkage phenomenon. We used the
 134 equation of Stewart et al. (2016) to model the variation of porosity due to
 135 one wetting-drying cycle for cracks porosity:

$$\phi_{\text{crack}} = (\phi_{\text{pedon}} - \phi_{\text{min}}) \left(\frac{1 - U^q}{1 - \varepsilon U^q} \right), \quad (2)$$

136 with $U = \Theta/\Theta_{\text{max}}$ and other parameters in Stewart et al. (2016).

137 Linking Stewart et al. (2016) equation with our framework:

$$f(\Theta) = \frac{\partial \phi_{\text{crack}}}{\partial t}. \quad (3)$$

138 We thus need to derivate ϕ_{crack} with time t :

$$f(\Theta) = \frac{[-qU(t)^{q-1}U'(t)(1 + \varepsilon U(t)^q)] - [q\varepsilon U(t)^{q-1}U'(t)(1 - U(t)^q)]}{(1 - \varepsilon U(t)^q)^2} \quad (4)$$

139 and $U'(t) = \partial\Theta/\partial t$

$$f(\Theta) = (1 - \varepsilon) \frac{[-qU(t)^{q-1}] - [2q\varepsilon U(t)^{2q-1}]}{(1 - \varepsilon U(t)^q)^2} \frac{\partial\Theta}{\partial t}, \quad (5)$$

140 where ε and q are fitting parameters.

141 *2.3. Changes in porosity due to the dynamics of roots population*

142 Roots have three different impacts on porosity:

- 143 • firstly, they fill some available porosity while they are appearing and
144 growing and then free up some pores when ageing and dying (by nar-
145 rowing) and disappearing (by degrading); this affects macroporosity;
- 146 • secondly, when they are growing, they compact the neighbouring soil
147 (rhizosphere) leading to a decrease of what Malamoud et al. (2009)
148 called aggregates porosity or the soil microporosity. The intensity of
149 compaction depends on either cracks exist before the appearance of
150 roots or not; however, Jangorzo et al. (2015) showed that roots prefer-
151 entially used existing pores like cracks when growing.
- 152 • third, when roots are degraded, they enter into the soil organic matter
153 turnover which also has another impact of soil porosity as demonstrated
154 by many authors (e.g. Coleman and Jinkinson, 1999; Malamoud et al.,
155 2009).

156 In this model we only consider the effect of roots on the dynamics of macro-
157 porosity by infilling.

158 Jangorzo (2013) and Jangorzo et al. (2015) have shown that the impact
159 of roots on macroporosity depends on the age category of the roots. When
160 young roots appear and then mature, they are growing thus leading to a
161 decrease in porosity. During ageing and degradation after death, they are
162 freeing some space which, by consequence lead to an increase in porosity.
163 Thus when roots age and become old roots the porosity increases. Thus, if
164 we consider the total surface fill by roots we can distinguish three different
165 age categories:

- 166 • surface with young root $R_y(t)$,
- 167 • surface with mature root $R_m(t)$,
- 168 • surface with old root $R_o(t)$,

169 The relationship between those three categories of the root population can
170 be modelled as shown in Figure 1. Here we consider there is no death of
171 young and mature roots. The computation of the root surface dynamics is

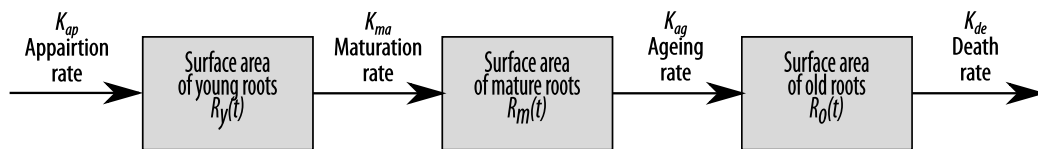


Figure 1: Conceptual model of the dynamic of root surface.
 Possibility to consider only two categories for the root population. κ function of time?

172 given by the following equations, with $R_y(t)$, $R_m(t)$ and $R_o(t)$, the surface
 173 areas occupied by young, mature, and old roots, respectively:

$$\frac{\partial R_y}{\partial t} = \kappa_{ap}(t) - \kappa_{ma}(t) \quad (6)$$

$$\frac{\partial R_m}{\partial t} = \kappa_{ma}(t) - \kappa_{ag}(t) \quad (7)$$

$$\frac{\partial R_o}{\partial t} = \kappa_{ag}(t) - \kappa_{de}(t), \quad (8)$$

174 with $\kappa_{ap}(t)$ the apparition rate of young roots, $\kappa_{ma}(t)$ the maturing rate of
 175 young roots, $\kappa_{ag}(t)$ the ageing rate of mature roots, and $\kappa_{de}(t)$ the death rate
 176 of old roots. No death of young and mature roots is considered. Thus the
 177 changes in the total surface occupied by roots is:

$$\frac{\partial R}{\partial t} = \kappa_{ap}(t) - \kappa_{de}(t) \quad (9)$$

178 The general equation for the changes in porosity due to the population
 179 dynamics of roots is function of $\kappa_{ap}(t)$, $\kappa_{ma}(t)$, $\kappa_{ag}(t)$, and $\kappa_{de}(t)$:

$$f(r) = -\kappa_{ap}(t) - \kappa_{ma}(t) + C_{ag}\kappa_{ag}(t) + \kappa_{de}(t). \quad (10)$$

180 This equation means that for each surface increase of young and mature
 181 roots there is a direct proportional loss of porosity. Reversibly, for each
 182 surface decrease of old roots by death, there is a direct proportional increase
 183 of porosity. When mature roots are ageing and become old, the consequence
 184 is the increase of porosity. dt_1 is the time elapsed between the moment the
 185 first root appears and the moment it starts narrowing. dt_2 is the time elapsed
 186 between dt_1 and the lifetime of the plant or roots. dt_3 is the time elapsed
 187 between dt_2 and the moment all dead roots disappeared or are degraded.
 188 This time is soil moisture and biological activity dependent. As young and

189 mature roots have the same effect on soil porosity, we include the young roots
 190 and mature by extending the time. The previous equation then becomes.

$$f(r) = -K_{ma}(dt_1) + K_{ag}(dt_2) + R_{de}(dt_3) \quad (11)$$

191 From equations 10, 6, 7, 8, ??, we can deduce:

$$f(r) = kR_o(t) - \kappa_{ap}(t) - \frac{\partial R_m}{\partial t}. \quad (12)$$

192 $R_y(t)$, $R_m(t)$ and $R_o(t)$ and their time derivatives can be obtained from
 193 the experimental data at each time step. If no experimental data are available
 194 general forms for $\kappa_{ap}(t)$, $\kappa_{ma}(t)$, and $\kappa_{ag}(t)$ must be proposed.

195 *2.4. Changes in porosity due to earthworms activity*

196 Jangorzo et al. (2013) showed that the intensity of earthworm activity
 197 increase soil porosity. This activity is function of i) the number of earthworm,
 198 ii) the quantity of organic matter and iii) the soil moisture. Many authors
 199 have described the soil organic matter turnover and models were developed.
 200 Among these models we can announce the RothC (Coleman and Jinkinson,
 201 1999), StructureC Malamoud et al. (2009) and a module in Vsoil (Lafolie
 202 et al., 2015). The general equation of porosity evolution according to the
 203 intensity of activity is as follows:

$$F(w) = k_{I_w} \times I_w \quad (13)$$

204

$$I_w = f(I_w^{\max} \times nb_w, \Theta, MO) \quad (14)$$

205 Where $F(w)$ is the rate of porosity changes due to worm activity; I_w is the
 206 total intensity of worm activity; I_w^{\max} is the maximal intensity of worm
 207 activity; ki_w is the conversion rate between the intensity of worm activity
 208 and the proportion of pore surface; nb_w is the number of earthworm; Θ
 209 is the soil moisture or water potential and MO is the soil organic matter.

210 *2.4.1. Worm activity in relation with soil humidity*

211 In relation to earthworm development and activity, soil humidity is better
 212 expressed as water potential due to the physiological characteristics of these
 213 organisms (Kretzschmar, 1991; Kretzschmar and Bruchou, 1991; Holmstrup,
 214 2001; Moreau-Valancogne et al., 2013). Some studies showed the influence

215 of water potential on earthworm development (Kretzschmar and Bruchou,
 216 1991; Holmstrup, 2001; Eriksen-Hamel and Whalen, 2006) and activity of
 217 earthworm (Kretzschmar, 1991; Hindell et al., 1994; Daniel et al., 1996). All
 218 those articles assess the development or the activity of *Aporrectodea spp.*,
 219 which are endogeic or anecic earthworms. Other factors can be tested in
 220 parallel (compaction, temperature). The earthworms activity is assessed via
 221 their cast production. Kretzschmar (1991); Hindell et al. (1994); Daniel et al.
 222 (1996) show the same pattern for the relationship between cast production
 223 and water potential: no or a negligible cast production for water potentials
 224 more negative than a base potential Ψ_b and then a linear increase of cast
 225 production with increasing water potential until $\Psi=0$. The estimated values
 226 of Ψ_b vary with species but indicate a narrow moisture tolerance range (Ta-
 227 ble 2.4.1). Ψ_b seem to vary with the ecological type: around -20– -40 kPa
 228 for anecic and around -10 kPa for endogeic.

Reference	Species	Ecological type	Ψ_b (kPa)
Kretzschmar (1991)	<i>Aporrectodea longa</i>	anecic	-40
Hindell et al. (1994)	<i>Aporrectodea rosea</i>	endogeic	-10
id.	<i>Aporrectodea caliginosa</i>	endogeic	-10
id.	<i>Aporrectodea caliginosa f. trapezoides</i>	endogeic	-5
Daniel et al. (1996)	<i>Aporrectodea nocturna</i>	anecic	-20

Table 1: Value of the base water potential, Ψ_b , measured by different authors.

229 The relationship between the activity of *Lumbricus castaneus* (epi-anecic
 230 worm, tested in Jangorzo (2013)) and the water potential shows the same
 231 pattern as identified for anecic earthworms in the literature. So we hypothe-
 232 sised that equations ?? and ?? can be inferred for *L. castaneus*. We assume
 233 that the normalised earthworm activity is proportional to the normalised cast
 234 production. Many equations were used to model the evolution of earthworms
 235 activity as function of water potential but we are interested in that issuing
 236 the cast production. For example Daniel et al. (1996) used an exponential
 237 equation to predict the evolution of cast production by *Aporrectodea nocturna*.

$$C^*(P) = he^{(Pi)} \quad \text{for} \quad -0.06\text{MPa} \leq P \leq 0\text{MPa} \quad (15)$$

238 where $C^*(P)$ is the transformed rate of cat production as a function of wa-
 239 ter potential in MPa and h and i are constants. They assumed that cast

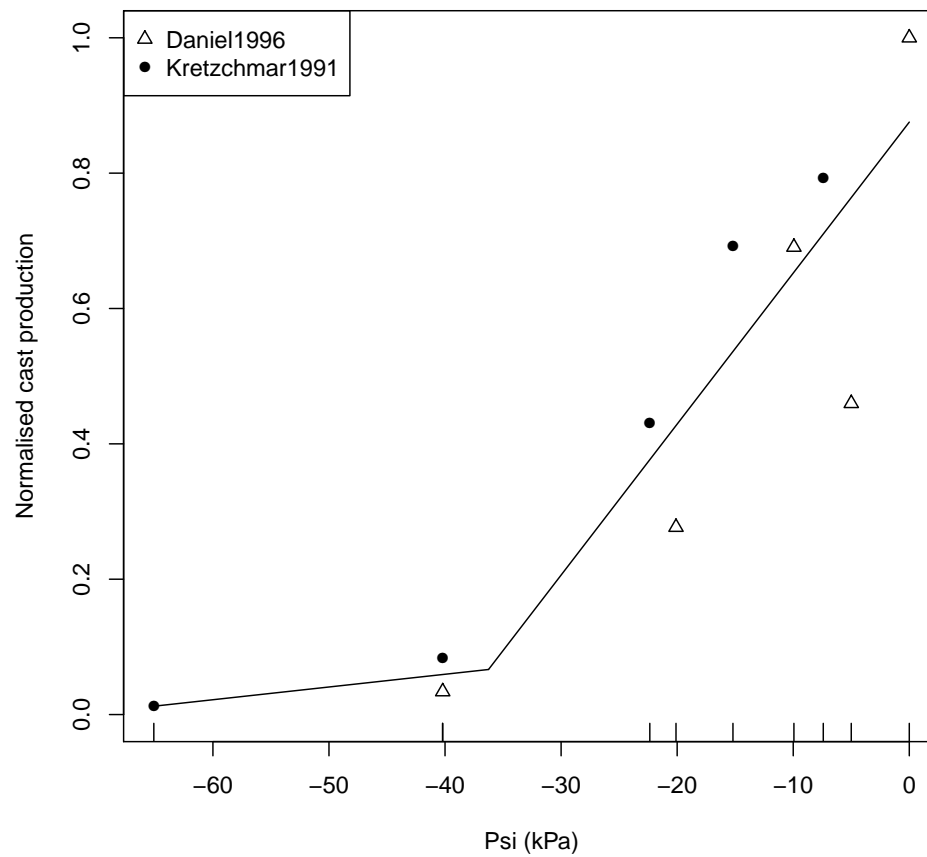


Figure 2: Model of the normalised cast production as a function of water potential for anecic earthworms. The data were extracted from Kretzschmar (1991) and Daniel et al. (1996). The fitted values are shown as points.

240 increased exponentially with the increase of water potential. Kaneda et al.
 241 (2016) on the other hand used the modified Gompertz function expressed as
 242 follows:

$$f(\Psi) = \zeta \exp^{-\left(\exp^{-(\Psi+\eta)/\theta}\right)} \quad \text{for} \quad -90.6\text{kPa} < P < -2\text{kPa} \quad (16)$$

243 where $f(P)$ stands for the soil aggregate formation rate-modifying factor for
 244 soil moisture as a function of water potential Ψ , in kilopascal ζ , η and θ are
 245 constant experimental coefficients determining slope of the curve. They use
 246 this function rather than Daniel's because their data showed a levelling-off
 247 near the water potential 0 kPa. In contrary, experimental data obtained
 248 by image analysis showed the increase of earthworm activity when water
 249 potential increases (Jangorzo, 2013; Jangorzo et al., 2015). We therefore
 250 used the Daniel's exponential equation to predict the evolution of earthworm
 251 activity. This relation could be formalized by the normalized cast production
 252 equation:

$$I_w(\Psi) = h e^{(\Psi i)} \quad (17)$$

253 Here we consider the casts production as a result of the intense activity of
 254 earthworm and this is proportional to the porosity production. However,
 255 when earthworms burrow, they dig, ingest soil particles mixed with organic
 256 matter that they excrete like casts. So, the cast produced are proportional to
 257 the void created in the soil. Say k_{I_w} the coefficient indicating the conversion
 258 between I_w and porosity. We assume that $0 < k_{I_w} < 1$ as it is a ratio between
 259 the I_w and the I_w^{max} . It means that not all the casts produced are equivalent
 260 to the porosity created.

261 2.4.2. *Worm activity in relation with number of earthworms*

262 Most of experiments were undertaken with a single individual of earth-
 263 worm. The effect of many individuals is not arithmetic but it has been shown
 264 that more the number of earthworm is high, greater is the intensity and so
 265 the porosity created (Jangorzo et al., 2015). However, 17 could be rearranged
 266 as follows:

$$I_w(\Psi) = n b_w \times h e^{(\Psi i)} \quad (18)$$

267 Where $n b_w$ is the number of earthworms

268 **2.4.3. Worm activity in relation with organic matter content**

269 Organic matter is used by earthworms for feeding and they burrow in
 270 order to find food. In this model, we assume that the organic matter content
 271 is constant as the quantity introduced in the system does not vary. However,
 272 the variation of earthworm activity as function of organic matter is equal to
 273 zero as well as that of soil temperature.

274 Combining the equations 13,14 and 18 we can write the general equation
 275 of porosity evolution as function of earthworms activity as follows:

$$F(w) = k_{I_w} \times nb_w \times he^{(\Psi_i)} \quad (19)$$

276 **2.5. Porosity disappearance**

277 We suggest that a proportion of the total porosity disappeared at each
 278 time step: Two processes induce porosity disappearance according to our
 279 assumption: i) water loading charge during wetting or watering and soil
 280 fauna (earthworms) when burrowing.

$$D_P = f(\Theta, I_w) \quad (20)$$

281 **2.5.1. Porosity disappearance due to watering**

282 When water is added in a structured soil, according to the stability of
 283 the soil, this water induce extinction of some aggregates. During water flow,
 284 these particles are transport deep in the soil through porosity. At the limit of
 285 water infiltration, these particles are deposited creating filings. This process
 286 lead to the decrease of porosity. However a successive watering without
 287 bioturbation lead undoubtedly to a disappearance of soil macropores. Say
 288 P_0 the porosity of the system at T_0 . After the first watering, the porosity
 289 decrease into P_1 at T_1 . After n series of watering we have a porosity of P_n .
 290 The total porosity that disappears is:

$$\Delta(P_\Theta) = \sum_1^n (P_{n+1} - P_n) \quad (21)$$

291 Where P is the porosity, n the number of watering series and the Θ means
 292 that the decrease is due to watering.

293 **2.5.2. Porosity disappearance due to earthworms activity**

294 In presence of earthworms, we assume that the decrease of porosity due
 295 to watering is null as during burrowing earthworm are willing to extract the

296 filings. The only action that decreases porosity is the deposit of casts in
 297 burrows. This action depends on how many times an earthworms passes in
 298 a burrow. Say P_0 the porosity of the system at T_0 . After the first passage
 299 (burrowing), the porosity decreases into P_1 at T_1 . After n series of burrowing
 300 we have a porosity of P_n . The total porosity that disappears is:

$$\Delta(P_w) = \sum_1^n (P_{n+1} - P_n) \quad (22)$$

301 Where P is the porosity, n the number of earthworm activity (burrowing)
 302 and the w means that the decrease is due to burrowing.

303 The solutions of equations 21 and 22 could be obtained using the least mean
 304 square methods as experienced by Daniel (1991); Daniel et al. (1996). The
 305 principle of least mean square method is formalized by (Stocker et al., 2002)
 306 which stipulates that: Given a function $y(x) = y(x; a)$ dependant on a pa-
 307 rameter a and n couples of values $(x_i; y_i)$, the optimal parameter a is defined
 308 by the Gauss function as follows:

$$\sum_i^n (y_i - y(x_i; a))^2 = Min_a \quad (23)$$

309 The idea behind this function is that it minimise the variable a and tends to a
 310 residual. In the case of our study, it means that the disappearance of porosity
 311 due to watering and earthworm activity is minimised. However the porosity
 312 decreases at each time step and at each watering, but due to the action of
 313 plants roots or burrowing, the decrease is compensate latter particularly by
 314 earthworms. This is why, unless this temporary decrease, the surface area of
 315 porosity increases with time. This can be formalised as follows:

316 *2.6. Submodels integration*

317 In our approach, we assumed that different factors acted successively in
 318 soil structuring. Beginning by the soil moisture which is the limiting factor
 319 to biological activity. Second plants find ideal conditions to develop and then
 320 soil fauna like earthworms. To maintain an equilibrium, a proportion of soil
 321 structure disappears due to the same structuring agents, primarily water.

322 Rearranging 1 we obtained:

$$\frac{dP}{dt} = [(I_w^{max} \times nb_w)^{-zv} \times \left\{ \begin{array}{l} 0,0224\psi + 0,8764, \text{ for } \psi < \Psi_b \\ 0,0019\psi + 0,1379, \text{ for } \psi > \Psi_b \end{array} \right\}] \quad (24)$$

$$+ [(3 + \eta_{ar}) - \frac{(D_{byr} + D_{bar} + D_{bor})}{D_s}] \quad (25)$$

$$+ [\int_1^n (\frac{\varepsilon + 1}{\varepsilon + \Theta^{-q}})] - D_P \quad (26)$$

323 3. Model implementation

324 An experiment was set up in a climate chamber where the effect of
 325 wetting-drying cycle, plant roots and earthworm activity on soil structure
 326 has been studied. This experiment was run during 14 months; images were
 327 recorded using Soilinsight (INRA, 2015), a dispositive of *insitu* monitoring
 328 of soil structure developed by Jangorzo (2013) and soil structure parameters
 329 were quantified by image analysis (Jangorzo et al., 2013, 2014, 2015). Three
 330 replicates of each factor were realized. The experimental design was fully de-
 331 scribed in Jangorzo (2013).

332 3.1. Initial conditions

333 At the beginning of the experiment $t = 0$, the surface areas of porosity
 334 and aggregates were quantified but the surface area of roots was null as well
 335 as the earthworm activity.

$$P(t = 0) = P_0 \quad (27)$$

$$r(t = 0) = 0 \quad (28)$$

$$I_w(t = 0) = 0 \quad (29)$$

336 3.2. Swelling-Shrinkage parameters

337 The mesocosm used in this experiment were filled with a constructed
 338 Technosol 500 μm sieved. The soil was made by a mixture of Treated Indus-
 339 trial Soil (TIS) and Paper mill-Sludge (PS). At the top of the cosm a thin
 340 layer of compost was layed out. Cosms were first moistened by capillarity
 341 uptake until saturation and gravimetric water content at field capacity was
 342 measured by weighing. Then four wetting-drying cycles where applied. After
 343 saturation, the system was let for drying until 20%. Then it is wetted un-
 344 til saturation and the excess water was collected as leachate. Regularly the

345 cosms were weighed to determine the water content. Based on these infor-
 346 mation the relation between matric potential and gravimetric water content
 347 was establish using hydrus. Images were analysed and cracks parameters
 348 were quantified.

349 3.3. Plant roots parameters

350 In other cosms, four seeds of *Lupinus albus* were sown and root devel-
 351 opment is monitored as described by Jangorzo et al. (2015). Fours days
 352 after the beginning of the experiment, the first roots appeared. Say D_1 this
 353 date. Roots continue growing during time and the surface is calculated by
 354 image analysis. By comparing different images generated, we identify the
 355 time when roots stop growing. Say D_2 this day. Then the dt_1 is deduced as
 356 follows : $dt_1 = D_2 - D_1$. The variation of roots surface according to time
 357 $\frac{\partial R_m}{\partial t}$ is calculated. The experiment continued running and at a moment plant
 358 roots were dead unless the system was watered. Say D_3 this date. The time
 359 elapsed during roots narrowing $dt_2 = D_3 - D_2$ is determined. Knowing that
 360 the total surface of dead roots is quantified, then the variation rate $\frac{\partial R_o}{\partial t}$
 361 is calculated. The rate of dead roots degradation is determined as soon as roots
 362 disappeared. This coefficient can also be determined using the equation of
 363 Lafolie used in Vsoil.

364 3.4. Earthworms activity parameters

365 In cosms containing plant roots, were introduced six individuals (nb_w) of
 366 *Lumbricus castaneus*. The soil moisture was maintained in a range between
 367 60% field capacity and 80% filed capacity. Using hydrus, this moisture con-
 368 tent is equivalent to a corresponding suction Ψ . As in the previous systems,
 369 images were generated each two hours what allows us to monitor the earth-
 370 worm activity. The different operations recorded are the number of visible
 371 actions made by a worm: i) creating a burrow, ii) filing a burrow, iii) en-
 372 larging burrow; iv) unchanged burrow ((Jangorzo et al., 2015). Then the
 373 intensity of earthworms activity I_w was determined knowing the number of
 374 individuals and the time elapsed. Moreover, image were analysed to quantify
 375 the evolution of soil porosity.

376 4. Conclusion and perspectives

377 Based on an innovative experimental set-up of soil observation and quan-
 378 tification, we proposed a conceptual model of soil porosity dynamics under

379 the influence of three aggregation factors. For this, three agents were exper-
 380 imented: wetting-drying cycle for environmental factor, *Lupinus albus* for
 381 plant roots and *Lumbricus castaneus* for soil fauna. To validate this model,
 382 it is important to set up a new experiment and resolve the different equations
 383 by computing them.

384 Appendix A. Variable definitions

385 All the variables used in the model are summarised in Table A.2.

Var.	Definition	Units	Source
a_{r_y}	Apparition rate of young roots	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
$A(t)$	Surface area of the soil aggregates in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
d_{r_d}	Degradation rate of dead roots	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
D_P	Destruction rate of the porosity	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	Literature review on soil compaction and collapse, experimental framework
θ	Rate of porosity changes due to soil humidity (wetting and drying cycles)	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
$f(w)$	Rate of porosity changes due to worm activity	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
$f(r)$	Rate of porosity changes due to root dynamics	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
I_w	Total intensity of worm activity	Number of worm actions per hour	Computed by image analysis from experimental data

Table A.2 – continued from previous page

Var.	Definition	Units	Source
I_w^{\max}	Maximal intensity of worm activity	Number of worm actions per hour and per individual	Computed by image analysis from experimental data Jangorzo (2013)
k	Factor of porosity destruction (collapse due to humidity)	Dimensionless	Calibration or literature review
k_{I_w}	Conversion rate between the intensity of worm activity and pore surface proportion	$\text{mm}^2 \times 10^{-2}$ mm^{-2} per worm action	
k_{r_d}	Conversion rate between the surface of degraded roots and the pore surface	Dimensionless	Calibration or computation from experimental data Jangorzo (2013)
k_{r_y}	Conversion rate between the surface area of new young roots and the pore surface area (proportion of porosity occupied by the surface area of new young roots)	Dimensionless	Calibration or computation from experimental data Jangorzo (2013)
$k_{r_y \rightarrow o}$	Conversion rate between the surface area of new old roots and the pore surface area	Dimensionless	Calibration or computation from experimental data Jangorzo (2013)
$k_{r_o \rightarrow d}$	Conversion rate between the surface area of new dead roots and the pore surface area	Dimensionless	Calibration or computation from experimental data Jangorzo (2013)

Table A.2 – continued from previous page

Var.	Definition	Units	Source
k_{Θ}	Conversion rate between humidity variations and pore surface proportion	$\text{mm}^2 \times 10^{-2}$ mm^{-2} per soil humidity unit	Literature review on shrinking, experimental framework
m_{r_d}	Death rate/mortality of old roots	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
MO	Soil organic matter content	$\text{g} \cdot \text{g}^{-1}$	Literature review
nb_w	Number of earthworms	Individuals	
$P(t)$	Surface area of the porosity ($> 50 \mu\text{m}$) in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
P_0	Surface area of the porosity ($> 50 \mu\text{m}$) in proportion to the total surface of the picture at the initial time $t = 0$	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
$R(t)$	Total surface area occupied by roots in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
$R_o(t)$	Surface area with old roots in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
$R_m(t)$	Surface area with mature roots in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)

Table A.2 – continued from previous page

Var.	Definition	Units	Source
$R_y(t)$	Surface area with young roots in proportion to the total surface of the picture	$\text{mm}^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
t	Time	Hour (h)	Experimental time step is 2 h for a total length of the experiment of 14 months
v_{r_y}	Ageing rate of young roots (conversion in old roots)	$\text{mm}^2 \times 10^{-2}$ $\text{mm}^{-2} \times \text{h}^{-1}$	
$\kappa_{d_r_d}$	Coefficient of root degradation (proportion of root degradation in relation to the population of dead roots)	h^{-1}	Calibration or literature review
Θ	Soil humidity or matric potential (Ψ)	Units in relation with the chosen variables	Literature review

Table A.2: Description of the used variables.
 Var. : Variables.

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