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 macroposity 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

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

of aggregates and voids. Many studies highlight the main fa[illegible] fluence soil structure and the five major of them are i) soil fa[illegible] roots, iii) environmental factors, iv) inorganic binding agents a[illegible]d v) soil microorganisms (Six et al., 2004). Research have been leaded t[illegible]o investigate the role of different agents on the evolution of structure. Plant roots influence soil structure in different ways but the most studied is by introducing organic matter. This process in widely investigated and some models have been proposed. For example, Roth-C study the soil organic matter turnover in non-waterlogged soils (Coleman and Jinkinson, 1999) and how this process is involved in soil structure (aggregation formation). Based on Roth-C, Malamoud et al. (2009) proposed a new model which studies the dynamics of soil structure (aggregation and porosity) named Structure-C. This model written in Mathlab consists of three sub models. An aggregation submodel, organic matter submodel and porosity submodel. The porosity submodel predicts the evolution of porosity during time under specific conditions of soil organic matter turnover.

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

Another phenomenon that influence soil porosity is the wetting-drying

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

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

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

2. Model theory

2.1. General model of soil porosity dynamics

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

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

2.2. Changes in porosity due to variations in soil humidity (wetting and drying cycles)

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

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

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

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

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

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

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

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

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

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

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

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

where ε and q are fitting parameters.

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

Roots have three different impacts on porosity:

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

In this model we only consider the effect of roots on the dynamics of macroporosity by infilling.

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

- surface with young root $R_y(t)$,
- surface with mature root $R_m(t)$,
- surface with old root $R_o(t)$,

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

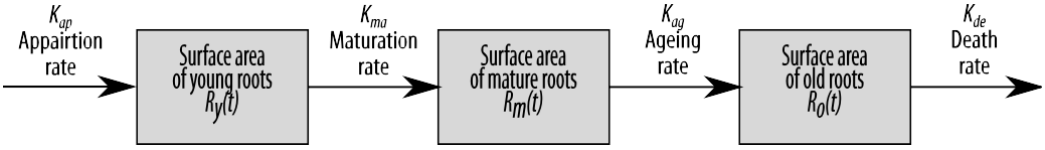

Figure 1: Conceptual model of the dynamic of root surface.
Possibility to consider only two categories for the root population. κ function of time?

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

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

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

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

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

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

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

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

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

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

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

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

$$f(\mathrm{r}) = kR_{\mathrm{o}}(t) - \kappa_{\mathrm{ap}}(t) - \frac{\partial R_{\mathrm{m}}}{\partial t}. \quad (12)$$

$R_{\mathrm{y}}(t)$, $R_{\mathrm{m}}(t)$ and $R_{\mathrm{o}}(t)$ and their time derivatives can be obtained from the experimental data at each time step. If no experimental data are available general forms for $\kappa_{\mathrm{ap}}(t)$, $\kappa_{\mathrm{ma}}(t)$, and $\kappa_{\mathrm{ag}}(t)$ must be proposed.

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

Jangorzo et al. (2013) showed that the intensity of earthworm activity increase soil porosity. This activity is function of i) the number of earthworm, ii) the quantity of organic matter and iii) the soil moisture. Many authors have described the soil organic matter turnover and models we [illegible] Among these models we can announce the RothC (Coleman a [illegible] 1999), StructureC Malamoud et al. (2009) and a module in [illegible] et al., 2015). The general equation of porosity evolution acc[illegible] intensity of activity is as follows:

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

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

Where $F(w)$ is the rate of porosity changes due to worm act[illegible] I_w is the total intensity of worm activity; $I_w max$ is the maximal inten[illegible] of worm activity; ki_w is the conversion rate between the intensity of v[illegible] and the proportion of pore surface; nb_w is the number of ear[illegible] the soil moisture or water potential and MO is the soil organi[illegible] matter.

2.4.1. Worm activity in relation with soil humidity

In relation to earthworm development and activity, soil hum[illegible] dity is better expressed as water potential due to the physiological character[illegible] organisms (Kretzschmar, 1991; Kretzschmar and Bruchou, 199[illegible] 2001; Moreau-Valancogne et al., 2013). Some studies showed [illegible]

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

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

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

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

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

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

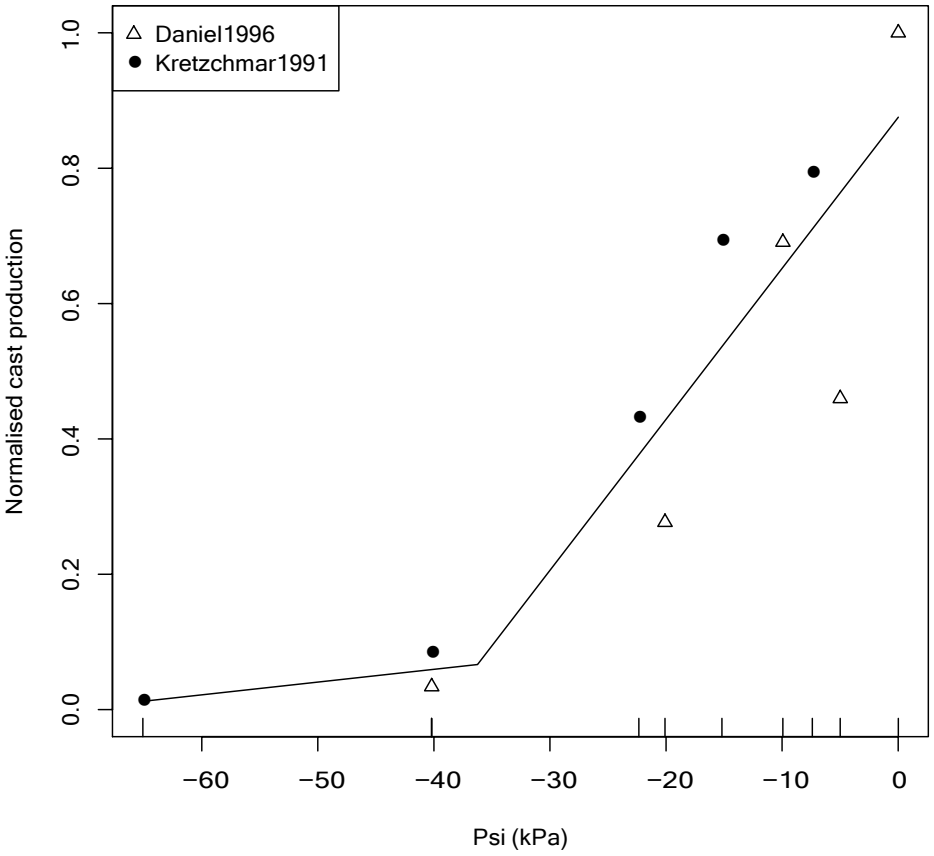

Figure 2: Model of the normalised cast production as a function of water potential for anecic earthworms. The data were extracted from Kretzschmar (1991) and Daniel et al. (1996). The fitted values are shown as points.

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:

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

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:

$$I_w(\Psi) = he^{(\Psi i)} \qquad (17)$$

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:

$$I_w(\Psi) = nb_w \times he^{(\Psi i)} \qquad (18)$$

267 Where nb_w is the number of earthworms

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

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

Combining the equations 13,14and 18 we can write the gen[illegible] of porosity evolution as function of earthworms activity as follo[illegible]

$$F(w) = k_{l\ w} \times nb_w \times he^{(\Psi i)} \quad (19)$$

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2.5. *Porosity disappearance*

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

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

2.5.1. *Porosity disappearance due to watering*

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

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

Where P is the porosity, n the number of watering series and the $_\Theta$ means that the decrease is due to watering.

2.5.2. *Porosity disappearance due to earthworms activity*

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

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

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

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

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

$$\sum_{i}^{n} (y_i - y(x_i; a))^2 = Min_a \quad (23)$$

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

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*2.6. **Submodels integration***

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

Rearranging 1 we obtained:

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

$$+[(3 + \eta_{ar}) - \frac{(D_b yr + D_b ar + D_b or)}{D_s}] \quad (25)$$

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

3. Model implementation

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

3.1. Initial conditions

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

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

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

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

3.2. Swelling-Shrinkage parameters

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

cosms were weighed to determine the water content. Based on these information the relation between matric potential and gravimetric water content was establish using hydrus. Images were analysed and cracks parameters were quantified.

3.3. Plant roots parameters

In other cosms, four seeds of *Lupinus albus* were sown and root development is monitored as described by Jangorzo et al. (2015). Fours days after the beginning of the experiment, the first roots appeared. Say D_1 this date. Roots continue growing during time and the surface is calculated by image analysis. By comparing different images generated, we identify the time when roots stop growing. Say D_2 this day. Then the dt_1 is deduced as follows : $dt_1 = D_2 - D1$. The variation of roots surface according to time $\frac{\partial R_m}{\partial t}$ is calculated.The experiment continued running and at a moment plant roots were dead unless the system was watered. Say D_3 this date. The time elapsed during roots narrowing $dt_2 = D_3 - D_2$ is determined. Knowing that the total surface of dead roots is quantified, then the variation rate $\frac{\partial R_o}{\partial t}$ is calculated. The rate of dead roots degradation is determined as soon as roots disappeared. This coefficient can also be determined using the equation of Lafolie used in Vsoil.

3.4. Earthworms activity parameters

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

4. Conclusion and perspectives

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

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

Appendix A. Variable definitions

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	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$A(t)$	Surface area of the soil aggregates in proportion to the total surface of the picture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
d_{r_d}	Degradation rate of dead roots	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
D_P	Destruction rate of the porosity	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	Literature review on soil compaction and collapse, experimental framework
ϑ	Rate of porosity changes due to soil humidity (wetting and drying cycles)	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$f(\mathrm{w})$	Rate of porosity changes due to worm activity	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$f(\mathrm{r})$	Rate of porosity changes due to root dynamics	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
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	$mm^2 \times 10^{-2}$ 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)
$k_{r_{y\to o}}$	Conversion rate between the surface area of new old roots and the pore surface area	Dimensionless	Calibration or computation from experimental data Jangorzo (2013)
$k_{r_{o\to d}}$	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	$mm^2 \times 10^{-2}$ mm^{-2} per soil humidity unit	Literature review on shrinking, experimental framework
m_{r_d}	Death rate/mortality of old roots	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
MO	Soil organic matter content	$g.g^{-1}$	Literature review
nb_w	Number of earthworms	Individuals	
$P(t)$	Surface area of the porosity (> 50 μm) in proportion to the total surface of the picture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysis on experimental data (Jangorzo, 2013)
P_0	Surface area of the porosity (> 50 μm) in proportion to the total surface of the picture at the initial time $t = 0$	$mm^2 \times 10^{-2}$ 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	$mm^2 \times 10^{-2}$ 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	$mm^2 \times 10^{-2}$ 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	$mm^2 \times 10^{-2}$ 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	$mm^2 \times 10^{-2}$ 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)	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
$\kappa_{d_{r_d}}$	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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