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Conceptual Modelling of the Dynamics of Soil Macroporosity Based on an in Situ and Direct Observation of Major Soil Structuring Agents During Early Stage of Pedogenesis

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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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 this study is, based on an in situ experiment including three major

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porosity factors, propose a conceptual 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. Results show that the evolution of macroporosity due to plant roots is linear and reachs its maximum at the end of the plant cycle. Earthworms create and destruct macroporosity during the up and down movement for food searching. At long term, the consequence of earthworm action results to an increase of macroporosity. Wetting and drying cycle has the same effect as earthworm. At the beginning, when soil shrinks, it leads to a creation of macroporosity that could be disturbed by swelling during soil humectation. Some soil particles migrate in the shrink and reduce the surface of macroporosity. When faced to many wetting drying cycles, the surface of macropores increase during time. Mathematical algorithms and computing are necessary to formalize this model and long-term experiment is needed to validate it.

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. [2]. 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 factors that in-fluence soil structure and the five major of them are i) soil fauna, ii) plant roots, iii) environmental factors, iv) inorganic binding agents and v) soil microorganisms [2]. Research have been leaded to 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 [3] and how this process is involved in soil structure (aggregation formation). Based on Roth-C, Malamoud et al. [4] 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.

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. [5]. 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 [6] 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 mod- ules 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 [4]. 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 stud- ies have been undertaken to study the process of soil cracking [7-12) and its impact on soil porosity [13,14]. In a recent work, Stewart et al. [15]

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 [16]. 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 [17]. Mechanism of reversible swelling-shrinkage strain and the Mechanism of irreversible swelling-shrinkage strain [17] shows the behaviour of soil volume during swelling-shrinkage cycle. This volume is assumed to be irreversible [18,5] 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) [19]. Earthworm, considered as ecosystem engineer [20] have been widely studied in the context of their role in soil structure. The efficiency of these engineers (activity), particularly earthworms depends on three fac- tors [21]. 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 [5]. Activity of earthworm is also conditioned by soil temperature and individual mass of the organism [22]. Based on laboratory and fieldexperiments, many models have been developed to predict the role of some earthworm species in soil aggregation (e.g. [22]) 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 [23,5]. 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 [24]. We could then assume that more food is available, greater is the burrowing activity. This assumption is modelled by Daniel [25] when he studied the effect of food consumption on aggregates formation. The degree of soil organic mat- ter transformation by earthworm is conceptualized and modelled by Chertov et al. [26] and Komarov et al. [27]. If the soil aggregate formation is known, it is not the case for the porosity existing in and between aggre- gates. 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; [28], 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 i) soil moisture $f(\Theta)$, ii) the population dynamics of roots $f(\mathrm{r})$, and iii) the earthworm activity $f(\mathrm{w})$ respectively, as well as a porosity disappearance term D_p :

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

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 [10, 29] BIOTECHNOSOL, others?). This shrinkage and swelling behaviour.

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 [30]. 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 [30]. Conversely, when the soil dries, it shrinks and its volume decreases which leads to an increase of soil bulk density [10], a decrease of aggregates porosity (microporosity), and an increase of shrinkage cracks (macroporosity) [15]. 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. [15] have proposed and validated a unified model to represent the variations of the different types of porosity with the changes in soil humidity. They consider three types of porosity:

In absence of any other agents, here we assume that the effect of microorganisms 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. [15] to model the variation of porosity due to one wetting-drying cycle for cracks porosity:

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

with $U = \Theta/\Theta_{\max}$ and other parameters in Stewart et al. [15].

Linking Stewart et al. [15] equation with our framework:

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

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

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

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

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

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. [4] 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. [5] 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.[3,4].

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

Jangorzo [24] and Jangorzo et al. [5] 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 $R_{\mathrm{m}}(t)$,
- surface with old root $R_{\mathrm{o}}(t)$,

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

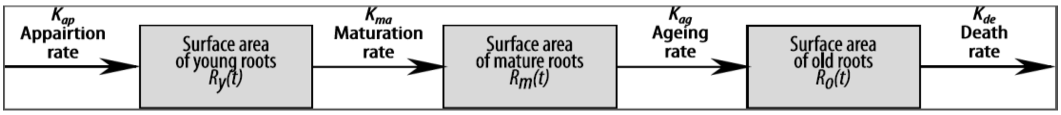

Fig. 1. Conceptual model of the dynamic of root surface.

Possibility to consider only two categories for the root population. κ function of time?

given by the following equations, with $R_y(t), R_{\mathrm{m}}(t)$ and $R_o(t)$, the surface areas occupied by young, mature, and old roots, respectively:

$$\frac{\partial R_{\mathrm{y}}}{\partial t} = \kappa_{\mathrm{ap}}(t) - \kappa_{\mathrm{maa}}(t) \quad (6)$$

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

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

with $\kappa_{\mathrm{ap}}(t)$ the apparition rate of young roots, $\kappa_{\mathrm{ma}}(t)$ the maturing rate of young roots, $\kappa_{\mathrm{ag}}(t)$ the ageing rate of mature roots, and $\kappa_{\mathrm{de}}(t)$ 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:

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

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

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

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 then becomes.

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

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

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

$R_y(t), R_{\mathrm{m}}(t)$ 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. [24] 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 were developed. Among these models we can announce the RothC [3], StructureC Malamoud et al. [4] and a module in Vsoil [6]. The general equation of porosity evolution according to the intensity of activity is as follows:

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

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

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

2.4.1 Worm activity in relation with soil humidity

In relation to earthworm development and activity, soil humidity is better expressed as water potential due to the physiological characteristics of these organisms [21,31,32,33]. Some studies showed the influence of water potential on earthworm development [31,32,34] and activity of earthworm [21,35,36]. 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 [21]; Hindell et al. [35]; Daniel et al. [36] 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 $\Psi = 0$. The estimated values of Ψ_{b} vary with species but indicate a narrow moisture tolerance range (Table 1). Ψ_{b} seem to vary with the ecological type: around $-20 - -40\mathrm{kPa}$ for anecic and around $-10\mathrm{kPa}$ for endogeic.

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

Reference	Species	Ecologic 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)	A porrectodea nocturna	anecic	-20

The relationship between the activity of Lumbricus castaneus (epi-anecic worm, tested in Jangorzo [24] 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. [36] used an exponential equation to predict the evolution of cast production by A porectodea nocturna.

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

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 increased exponentially with the increase of water potential. Kaneda et al. [22] on the other hand used the modified Gompertz function expressed as follows:

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

where $f(P)$ stands for the soil aggregate formation rate-modifying factor for soil moisture as a function of water potential Ψ, in kilopascal ζ, η and θ are constant experimental coefficients determining slope of the curve. They use this function rather than Daniel's because their data showed a levelling-off near the water potential 0kPa. In contrary, experimental data obtained by image analysis showed the increase of earthworm activity when water potential increases [24,5]. We therefore used the Daniel's exponential equation to predict the evolution of earthworm activity. This relation could be formalized by the normalized cast production equation:

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

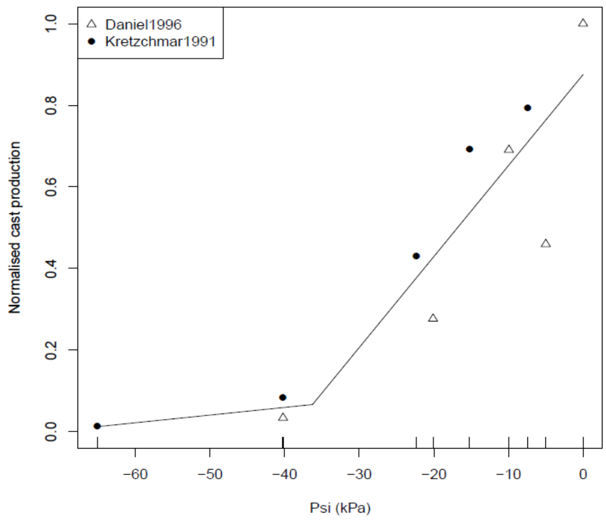

Fig. 2. Model of the normalised cast production as a function of water potential for anecic earthworms. The data were extracted from Kretzschmar [21] and Daniel et al. [36]. The fitted values are shown as points

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

2.4.2 Worm activity in relation with number of earthworms

Most of experiments were undertaken with a single individual of earthworm. The effect of many individuals is not arithmetic but it has been shown that more the number of earthworm is high, greater is the intensity and so the porosity created [5]. However, 17 could be rearranged as follows:

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

Where nb_w is the number of earthworms

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

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

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 [36]. The principle of least mean square method is formalized by [37] 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:

$$\sum_i^n \left(y_i - y(x_i; a)\right)^2 = \mathrm{Min}_a \quad (23)$$

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:

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:

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

$$+ \left[(3 + \eta_{ar}) - \frac{(D_{byr} + D_b ar + D_b or)}{D_s} \right] \quad (25)$$

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

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 [38], a dispositive of in situ monitoring of soil structure developed by Jangorzo [24] and soil structure parameters were quantified by image analysis [5,16,24].Three replicates of each factor were realized. The experimental design was fully described in Jangorzo [24].

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 $500\mu m$ 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. [5]. 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 $\Psi.As$ 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 [5]. 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 imented: 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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Vereecken H, Schnepf A, Hopmans JW, Javaux M, Or D, Roose T, Vanderborght J, Young MH, Amelung W, Aitkenhead M, Allison SD. Modeling soil processes: Review, key challenges, and new perspectives. Vadose zone journal. 2016 May 1;15(5).
2. Six J, Bossuyt H, Degryze S, Denef K. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil and tillage research. 2004 Sep 1;79(1):7-31.
3. Coleman K, Jenkinson DS. RothC-26.3: A Model for the Turnover of Carbon in Soil, Model Description and Windows User Guide. IACR-Rothamsted, Harpenden, UK. 1999.
4. Malamoud K, McBratney AB, Minasny B, Field DJ. Modelling how carbon affects soil structure. Geoderma. 2009 Feb 15;149(1-2):19-26.
5. Jangorzo NS, Watteau F, Hajos D, Schwartz C. Nondestructive monitoring of the effect of biological activity on the pedogenesis of a Technosol. Journal of Soils and Sediments. 2015 Aug;15: 1705-15. Available:https://doi.org/10.1007/s11368-014-1008-z
6. Lafolie F, Cousin I, Mollier A, Pot V, Maron PA, Moitrier N, Nouguier C, Moitrier N, Beudez N. Which benefits in the use of a modeling platform: The VSoil example. InEGU General Assembly Conference Abstracts 2015 Apr (p. 5886).
7. Konrad JM, Ayad R. A idealized framework for the analysis of cohesive soils undergoing desiccation. Canadian Geotechnical Journal. 1997 Aug 1;34(4):477-88. Available:https://doi.org/10.1139/t97-015
8. Greco R. Preferential flow in macroporous swelling soil with internal catchment: model development and applications. Journal of Hydrology. 2002 Dec 15;269(3-4):150-68. Available:http://www.sciencedirect.com/science/article/pii/S0022169402002159
9. Braudeau E, Mohtar RH. Modeling the swelling curve for packed soil aggregates using the pedostructure concept. Soil Science Society of America Journal. 2006 Mar;70(2):494-502. Available: https://dl.sciencesocieties.org/publications/sssaj/abstracts/70/2/494
10. Peng X, Horn R. Anisotropic shrinkage and swelling of some organic and inorganic soils. European Journal of Soil Science. 2007 Feb;58(1):98-107. Available:http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2389.2006.00808.x/abstract
11. Chertkov VY. An integrated approach to soil structure, shrinkage, and cracking in samples and layers. Geoderma. 2012 Mar 1;173:258-73. Available:http://www.sciencedirect.com/science/article/pii/S0016706112000341
12. Chertkov VY. Physical modeling of the soil swelling curve vs. the shrinkage curve. Advances in water resources. 2012b Aug 1;44:66-84. Available:http://www.sciencedirect.com/science/article/pii/S0309170812001078
13. Coppola A, Gerke HH, Comegna A, Basile A, Comegna V. Dual-permeability model for flow in shrinking soil with dominant horizontal deformation. Water Resources Research. 2012 Aug;48(8) W08527. Available:http://onlinelibrary.wiley.com/doi/10.1029/2011WR011376/abstract

14. Coppola A, Comegna A, Dragonetti G, Gerke HH, Basile A. Simulated preferential water flow and solute transport in shrinking soils. Vadose Zone Journal. 2015 Sep 1;14(9):vzj2015-02. https://dl.sciencesocieties.org/publications/vzj/abstracts/14/9/vzj2015.02.0021
15. Stewart RD, Rupp DE, Abou Najm MR, Selker JS. A unified model for soil shrinkage, subsidence, and cracking. Vadose Zone Journal. 2016 Mar 1;15 (3).
16. Jangorzo NS, Schwartz C, Watteau F. Image analysis of soil thin sections for a non-destructive quantification of aggregation in the early stages of pedogenesis. European Journal of Soil Science. 2014 Jul;65(4):485-98. Available:http://dx.doi.org/10.1111/ejss.12110
17. Wang G, Wei X. Modeling swelling–shrinkage behavior of compacted expansive soils during wetting–drying cycles. Canadian Geotechnical Journal. 2015;52(6):783-94. Available:http://www.nrcresearchpress.com/doi/abs/10.1139/cgj-2014-0059
18. Tessier D. Étude expérimentale de l'organisation des matériaux argileux-Hydratation, gonflement et structuration au cours de la dessication et de la réhumectation. 1984.
19. Croney D, Coleman JD. Soil structure in relation to soil suction (pF). Journal of soil science. 1954 Jan;5(1):75-84. Available:http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2389.1954.tb02177.x/abstract
20. Jones, C. G., Lawton, J. H., Shachak, M., 1994. Organisms as Ecosystem Engineers. In: Ecosystem Management. Springer, New York, NY, pp.130–147, dOI: 10.1007/978-1-4612-4018-1 14. Available:https://link.springer.com/chapter/10.1007/978-1-4612-4018-1_14
21. Kretzschmar A. Burrowing ability of the earthworm Aporrectodea longa limited by soil compaction and water potential. Biology and fertility of soils. 1991 Apr;11:48-51. Available:https://link.springer.com/article/10.1007/BF00335834
22. Kaneda S, Ohkubo S, Wagai R, Yagasaki Y. Soil temperature and moisture-based estimation of rates of soil aggregate formation by the endogeic earthworm Eisenia japonica (Michaelsen, 1892). Biology and Fertility of Soils. 2016 Aug;52:789-97. Available:https://link.springer.com/article/10.1007/s00374-016-1119-3
23. Zangerlé A, Pando A, Lavelle P. Do earthworms and roots cooperate to build soil macroaggregates? A microcosm experiment. Geoderma. 2011 Nov 1;167:303-9. Available:http://www.sciencedirect.com/science/article/pii/S0016706111002709
24. Jangorzo NS, Watteau F, Schwartz C. Evolution of the pore structure of constructed Technosols during early pedogenesis quantified by image analysis. Geoderma. 2013 Oct 1;207:180-92. Available:http://www.sciencedirect.com/science/article/pii/S0016706113001705
25. Daniel O. Leaf-litter consumption and assimilation by juveniles of Lumbricus terrestris L.(Oligochaeta, Lumbricidae) under different environmental conditions. Biology and Fertility of Soils. 1991 Dec;12:202-8. Available:https://link.springer.com/article/10.1007/BF00337203
26. Chertov O, Shaw C, Shashkov M, Komarov A, Bykhovets S, Shanin V, Grabarnik P, Frolov P, Kalinina O, Priputina I, Zubkova E. Romul_Hum model of soil organic matter formation coupled with soil biota activity. III. Parameterisation of earthworm activity. Ecological Modelling. 2017 Feb 10;345:140-9. Available:http://www.sciencedirect.com/science/article/pii/S0304380016302368
27. Komarov A, Chertov O, Bykhovets S, Shaw C, Nadporozhskaya M, Frolov P, Shashkov M, Shanin V, Grabarnik P, Priputina I, Zubkova E. Romul_Hum model of soil organic matter formation coupled with soil biota activity. I. Problem formulation, model description, and testing. Ecological Modelling. 2017 Feb 10;345:113-24. Available:http://www.sciencedirect.com/science/article/pii/S0304380016303088
28. Jangorzo, S. N., Feb. 2013. Quantification du processus d’agr´egation dans les Technosols. Ph.D. thesis, Universit´e de Lorraine, Nancy. Available:http://www.theses.fr/2013LORR0004
29. Huot H, Simonnot MO, Watteau F, Marion P, Yvon J, De Donato P, Morel JL. Early transformation and transfer processes in a Technosol developing on iron industry

deposits. European journal of soil science. 2014 Jul;65(4):470-84.
Available:http://dx.doi.org/10.1111/ejss.12106

30. Smiles DE. Hydrology of swelling soils: a review. Soil Research. 2000;38(3):501-21.
Available:http://www.publish.csiro.au/sr/SR99098

31. Kretzschmar A, Bruchou C. Weight response to the soil water potential of the earthworm Aporrectodea longa. Biology and fertility of soils. 1991 Dec;12:209-12.
Available:https://link.springer.com/article/10.1007/BF00337204

32. Holmstrup M. Sensitivity of life history parameters in the earthworm Aporrectodea caliginosa to small changes in soil water potential. Soil Biology and Biochemistry. 2001 Jul 1;33(9):1217-23.
Available:http://www.sciencedirect.com/science/article/pii/S0038071701000268

33. Moreau-Valancogne P, Bertrand M, Holmstrup M, Roger-Estrade J. Integration of thermal time and hydrotime models to describe the development and growth of temperate earthworms. Soil Biology and Biochemistry. 2013 Aug 1;63:50-60.

34. Eriksen-Hamel NS, Whalen JK. Growth rates of Aporrectodea caliginosa (Oligochaetae: Lumbricidae) as influenced by soil temperature and moisture in disturbed and undisturbed soil columns. Pedobiologia. 2006 Jul 3;50(3):207-15.
Available:http://www.sciencedirect.com/science/article/pii/S0031405605001356

35. Hindell RP, McKenzie BM, Silvapulle MJ, Tisdall JM. Relationships between casts of geophagous earthworms (Lumbricidae, Oligochaeta) and matric potential: I. Cast production, water content, and bulk density. Biology and fertility of soils. 1994 Jul;18:119-26.

36. Daniel O, Kohli L, Schuler B, Zever J. Surface cast production by the earthworm *Aporrectodea nocturna* in a pre-alpine meadow in Switzerland. Biology and fertility of soils. 1996 Apr;22:171-8.

37. Stocker, H., Bosser, V., Marcello, S., 2002. Toutes les math´ematiques et les bases de l’informatique, 2002nd Edition. Dunod, Paris.
Available:https://www.dunod.com/sciences-techniques/toutes-mathematiques-et-bases-informatique

38. INRA, May 2015. Soilinsight® : Un voyage au cœur des sols.
Available:http://www.nancy.inra.fr/Toutes-les-actualites/Soilinsight-R

APPENDIX A. VARIABLE DEFINITIONS

All the variables used in the model are summarised in Table A.1.

Table A.1. Description of the used variables.Var.: Variables.

Var.	Definition	Units	Source
a_{ry}	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 pic- ture	$mm^2 \times 10^{-2}\ mm^{-2}$	Obtained by image analysison experimental data (Jangorzo, [5])
d_{rd}	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 re- view on soilcompaction and collapse,experimental framework
θ	Rate of porosity changes due to soil humidity (wet-ting and drying cycles)	$mm^2 \times 10^{-2}\ mm^{-2} \times h^{-1}$	
$f(w)$	Rate of porosity changes due to worm activity	$mm^2 \times 10^{-2}\ mm^{-2} \times h^{-1}$	
$f(r)$	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 analysisfrom experimental data

Table A.1 – 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 analysisfrom experimental data Jangorzo [24]
k	Factor of porosity destruction (collapse due to humidity)	Dimensionless	Calibration or literature review
k_{Iw}	Conversion rate between the intensity of worm activity and pore surface proportion	$mm^2 \times 10^{-2}\ mm^{-2}$ per wormaction	
k_{rd}	Conversion rate between the surface of degradedroots and the pore surface	Dimensionless	Calibration or computation from experi- mental data Jangorzo [24]
k_{ry}	Conversion rate between	Dimensionless	Calibration or

Var.	Definition	Units	Source
	the surface area of new young roots and the pore surface area (proportion ofporosity occupied by the surface area of new youngroots)		computation from experi-mental data Jangorzo [24]
$k_{ry \to o}$	Conversion rate between the surface area of new old roots and the pore surfacearea	Dimensionless	Calibration or computation from experi-mental data Jangorzo [24]
$k_{ro \to d}$	Conversion rate between the surface area of new deadroots and the pore surfacearea	Dimensionless	Calibration or computation from experi-mental data Jangorzo [24]

Table A.1 – continued from previous page

Var.	Definition	Units	Source
k_{Θ}	Conversion rate between humidity variations andpore surface proportion	$mm^2 \times 10^{-2}$ mm^{-2} per soilhumidity unit	Literature review on shrinking, ex-perimental framework
m_{rd}	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 re-view
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 analysison experimental data [24]
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 analysison experimentaldata [24]
$R(t)$	Total surface area occupied by roots in proportion to the total surface of the pic- ture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysison experimentaldata [24]
$R_o(t)$	Surface area with old roots in proportion to the totalsurface of the picture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysison experimentaldata [24]
$R_m(t)$	Surface area with mature roots in proportion to thetotal surface of the picture	$mm^2 \times 10^{-2}$ mm^{-2}	Obtained by image analysison experimentaldata [24]

Table A.1 – 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 byimage analysison experimentaldata [24]
t	Time	Hour (h)	Experimental time step is 2 h for a total length of the experiment of 14 months
v_{ry}	Ageing rate of young roots (conversion in old roots)	$mm^2 \times 10^{-2}$ $mm^{-2} \times h^{-1}$	
κ_{drd}	Coefficient of root degra-dation (proportion of root degradation in relation tothe population of dead roots)	h^{-1}	Calibration orliterature review
Θ	Soil humidity or matric po-tential (Ψ)	Units in relationwith the chosen variables	Literature re-view

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