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How lysimetric monitoring of Technosols can contribute to understand the temporal dynamics of the soil porosity

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ABSTRACT

Soil poral architecture controls soil functioning and is submitted to temporal changes. The monitoring of soil structure dynamics is complicated by inherent technical constraints in its measurement that are either punctual or complex. In this study, four soils, from a natural one to incrementally anthropized (including three Technosols: Spolic Toxic, Terric Transportic, Spolic Garbic Hydric), have been studied. Seven 2-m^3 lysimetric columns have been setup to compare planted and non-planted treatments over 3 to 6 years. Data on the water balance and the hydrodynamics were continuously acquired. Differences were observed between the various soils as a function of their texture. The presence of vegetation also led to significant differences, especially in hot periods, between the vegetated and the bare soils treatments: the amount of water stored into the soil was up to 210 L m^{-2} higher for bare soil. Furthermore, the analysis of the "critical water storage capacity" highlighted differences in the hydrodynamics at two time scales. For vegetated soils, similar seasonal variations depending on the climatic conditions were observed for all soils, with higher S_{CRIT} values in cold periods compared to hot periods (differences were up to 190 L m^{-2}). These results were attributed to roots development over the climatic year that decreases water storage capacity and increases preferential flows. Besides, significant trend evolution was also observed but only for the youngest *i.e.* the most anthropized soils. Their total water storage capacity decreased down to 52%. It is possibly due to soil compaction, the increase of pore connectivity related to root development and the formation of organo-mineral associations. Our work promotes the association of monitored lysimeters as tool and the study of soils within a gradient of anthropization in order to describe a pedogenetic process like the dynamics of soil porosity.

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1. Introduction

Soil structure and porosity, as defined by Oades (1984), are key components of soil health and functioning. Actually water and gas flows, solute transport, and biological activity are directly affected by the geometry of the available pore space (Angers and Caron, 1998; Vogel and Roth, 2001; Strudley et al., 2008; Alaoui et al., 2011). Soils pore size distribution and their connectivity influence many aspects of the soil functioning. Macroporosity contributes to water flows in wet periods, whereas microporosity is involved in water and solutes exchanges, even during dry periods (Jarvis, 2007; Lipiec et al., 2012). Natural factors such as climate and biological activity or human actions through tillage, fertilization, drainage or compaction induce significant temporal changes of the soil pore system (Alaoui and Helbling, 2006; Jarvis, 2007; Montagne et al., 2009; Schwen et al., 2011a, 2011b; Jangorzo et al., 2013; Dal Ferro et al., 2013; Mora and Lazaro, 2014).

Soil pore architecture is not a static property. Actually, the whole soil system is governed by external and internal forces that contribute to its evolution (Cocos, 1997). A two-tier evolution has been recently proposed: i) fast and cyclic — smartly entitled as "soil beats" by Mora and Lazaro (2014) — due to seasons and growing cycles; ii) slow and steady — due to pedogenesis (Séré et al., 2012). The changes of pore architecture over short term have been shown under the influence of wetting-drying cycles as well as during vegetative and seasonal cycles (Farkas et al., 2006; Mora and Lazaro, 2014). A decrease of the macroporosity at the soil surface due to rainfall has been explicitly assessed by Sandin et al. (2017). It has also been demonstrated that soil compaction leads to a global decrease of total porosity even if its impact on the different sizes of pores is notably related in a complex way with soil depth (Lipiec et al., 2012). The seasonal variability of hydraulic properties, and consequently of the soil porosity, is large. For example, in a tilled soil, the values of the saturated water content measured at the beginning and the end of the vegetation period can differ significantly from 0.37 to 0.49 m^3 m^{-3} (Farkas et al., 2006; Schwen et al., 2011a, 2011b). In the same context, Das Gupta et al. (2006) found that, while the relationships between soil hydraulic conductivity and

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matrix potential at different locations of an experimental plot do not show any significant spatial variability, they display a strong temporal variation. This variation is due to the evolution of natural environmental conditions linked with the seasonal rainfall and the root growth. As reviewed by Angers and Caron (1998), root development affects the soil in two ways: evolution of the solid phase properties (*i.e.* enrichment in rhizodeposits, modification of pH, biological activity stimulation) (Morel et al., 1991; Philippot et al., 2013) and changes in the structure (*e.g.* saturated hydraulic conductivity increased from 5.10^{-6} m s^{-1} before the growth of roots, to 9.10^{-6} m s^{-1} after the growth) (Powis, 2001). Indeed, as roots grow they compress the soil around them, increasing the bulk density and decreasing the porosity up to 24% (Bruand et al., 1996). They also induce changes in the pore size distribution: a decrease of the macroporosity together with an increase of the microporosity has been observed (Jangorzo et al., 2013). Once the roots mature and die, they leave channels of continuous macropores also called biopores (Volkmar and Entz, 1995). These root-induced pores go deep into the soil profile and lead to an increase of the number of continuous macropores. Similar observations have been described in link with biological activity (Milleret et al., 2009; Bottinelli et al., 2010; Jangorzo et al., 2014). Longer-term changes of soil structure are widely studied in soil science. Lin (2010) notably theorized such an evolution in terms of thermodynamic entropy, expressing the fact that the formation over time of aggregates, horizons, and profiles represent more and more ordered states. Thus, pore architecture is a soil property that evolves over time, at different time scales, under the influence of weather seasonality, vegetative and biological cycles, but also in the course of pedogenesis.

The experimental monitoring of soil porosity dynamics is still impaired by inherent technical constraints. The main approach remains the destructive sampling of either bulk soil (Bottinelli et al., 2010), soil cores (Hartge and Horn, 2009; Dal Ferro et al., 2013; Jirků et al., 2013; Mora and Lazaro, 2014; Naveed et al., 2014), kubiena boxes (Jangorzo et al., 2013), or even incubated mesocosms (Garbout et al., 2013). All of these solutions are one-time as samples are taken. This is a major drawback, but samples can then be fully characterized either in a direct (*e.g.* physical analysis, X-ray computed tomography) or indirect way (*e.g.* water retention curve) in order to estimate, in a very efficient way, physical parameters such as bulk density, total porosity, pore size distribution, hydraulic parameters, or morphological features. Fewer works emphasize on non-destructive measurements such as tension infiltrometer (Schwen et al., 2011a, 2011b) or laser scanner to investigate soil surface porosity (Cheng et al., 2012). A promising approach is the continuous monitoring of soil moisture with time-domain reflectometry (TDR) probes that can be coupled with inverse modelling approach to estimate soil hydraulic parameters (Alaoui and Helbling, 2006; Séré et al., 2012; Cannavo et al., 2014). However, this approach requires a complex and somewhat arbitrary treatment of the signal, which leads to calibration problems as well as the necessity to state hypotheses on soil heterogeneity and roots development. In an interesting and innovative way Jangorzo et al. (2015) designed an original device that can acquire high resolution soil images in order to get some pore morphological features.

Additionally, the study of Technosols - highly anthropized soils (IUSS, 2014) - was found to be very promising as they are submitted to a fast and intense pedogenesis (Huot et al., 2015a, 2015b; Leguédois et al., 2016). As a study model, they enable the monitoring of significant evolution of soil properties – including soil porosity – within a short period of time (*i.e.* less than a decade) (Séré et al., 2010).

The present work is based on an *in situ* and middle term (3 to 6 years) lysimetric monitoring and aims at understanding soil structure evolution resulting from seasonal climatic variations, vegetation cycling and early pedogenic evolution. Lysimeters have been abundantly used to monitor soil leaching processes and element fluxes (see for example Rowland and Haygarth, 1997 and Ineson et al., 1998). The originality here first lies in the continuous acquisition of data on soil hydrodynamics, as a proxy of soil structure. The innovative approach is also on the variety of soils - within a large anthropization gradient - that were studied. The chosen soils were highly contrasted in terms of entropy (Lin, 2011), which is interpreted as their ability to evolve over time: the more the soil is anthropized and young, the faster and the more its properties will evolve with time (Leguédois et al., 2016).

2. Materials and methods

2.1. Description of the soils

2.1.1. Soil selection

The soils were chosen among the 24 existing lysimeters of the GISFI experimental station (http://www.gisfi.fr) that were implemented for previous research programs. The selection took into account the following parameters: the age of the soil (i.e. the time at which the soil materials have been exposed to external factors such as climate and biological activity), the nature of the soil's parent material(s), the origin and past land use(s), the date of setup and the nature and extent of vegetation cover. As a result, the four selected soils exhibited very different features, considering their level of anthropization, their origin and their age (Table 1).

2.1.2. Soil origins and classifications

The soils were classified according to the WRB (IUSS Working Group WRB, 2014) (Table 1). The Cambic Stagnic Luvisol (L) was sampled in Noyelles-Godault (50.4174° N, 2.9611° E; North of France) and was used for crop farming (Sterckeman et al., 2000). It was developed on alluvial deposits and, as a natural soil, was considered as a control. The Spolic Toxic Technosol (T1) was sampled in Neuves-Maisons (48.6163° N, 6.0908° E; North-East of France), on a former coking plant that ceased its activity in the beginning of the nineties. The soil exhibited a residual contamination (PAH, hydrocarbons) (Monserie et al., 2009; Ouvrard et al., 2011). The Terric Transportic Technosol (T2) resulted in the mixing of different soil materials (from unknown origins) contaminated by organic pollutants. This Technosol was treated by an environmental company, through bioremediation during four months, after the addition of fertilizers and air injection. The Spolic Garbic Hydric Technosol (T3) was constructed for pedological engineering purposes. It was composed of three layers or soil horizons made of green waste compost, papermill sludge, and thermally treated soil; it was fully described in Séré et al. (2008). T3 was constructed just before its setup in lysimeter.

2.1.3. Physical and pedological properties

The bulk densities were measured during the lysimeter setup (Table 2). The soil L was composed of four distinct genetic horizons. The soils T1 and T2 were both made of a unique parent material. And the soil T3 was constructed with three distinct horizons that were previously described (Séré et al., 2008). The texture analyses (five size fractions with decarbonation; AFNOR, 2003) of all horizons were carried out by the certified laboratory of INRA (Laboratoire d'Analyse des Sols, INRA, Arras). The textural classes of the soils have been determined following the United States Department of Agriculture (USDA, 1975) (Table 2). Note that all soils exhibited essentially a sandy to silty-sandy texture.

2.2. Lysimetric monitoring

2.2.1. Lysimeter setup

As mentioned, the lysimetric station is located on the GISFI experimental station (Homécourt, 49.2246° N, 5.9756° E; North-East of France) and was supplied by Umwelt-Gerate-Technik (UGT, Müncheberg, Germany). The experimental devices consist of 2-m-deep and 1-m^2-surface-area columns. The columns were either sampled *in situ* (lysimeter sampling technique developed by UGT to sample soils without any disturbance, Patent No. 10 353 485; 10 2011 006374)

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