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Evolution of the pore structure of constructed Technosols during early pedogenesis quantified by image analysis

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ABSTRACT

Despite Technosols being widely present in environments, their pedogenesis has been studied to a much lesser extent than "natural" soils. As the initial characteristics of constructed Technosols are controlled and well-known, they represent unique experimental models for studying the early stages of soil formation. Focusing on those processes involved in soil structuration, our study proposes an image analysis protocol for the quantification of porosity and the study of pore system architecture evolution. The implications that the architecture of soil pore system evolution could have on the capacity of these constructed soils as well as "natural" soils to carry out their basic functions are also discussed. Soils with porosities of >50 μm and 0.5–50 μm were directly quantified by analyzing thin section images prepared from undisturbed soil samples, collected *in situ* in Kubiena boxes in 2008 and 2010. Pores were classified according to their diameter (five classes: diameter > 2000 μm, 500–2000 μm; 50–500 μm; 25–50 μm; and 0.5–25 μm). The >50 μm porosity decreased significantly between 2008 (20.60% ± 6.10) and 2010 (14.36% ± 5.35). Only the number and surface of large pores (packing pores) with equivalent diameters exceeding 2000 μm decreased. The surface of 0.5–50 μm porosity increased between 2008 (10.56 ± 2.64) and 2010 (13.63 ± 2.55). This means that the soil is compacting. The consequence of this is a reduction of water holding capacity, which has a bearing on the filtering/buffering function of soil. After statistical analysis, the number of pores (N), surface area (A), index of connectivity (Ic) and shape factor (Sf) are proposed as indicators to be monitored in the study of Technosol porosity evolution.

1. Introduction

Technosols are anthropogenic soils and present agronomical and toxic properties differing from classical (*e.g.* forest and agricultural) soils (Lefort, 2009). If the composition of Technosols is, by definition different to so-called natural soils (IUSS Working Group WRB, 2006), it has not been clearly demonstrated that their pedogenesis is specific. Therefore, it is important to know how they function and to which state they will evolve over a period of time. A soil's physicochemical characteristics and structure in particular influence these functions. Indeed, soil structure, through the soil pore architecture, influences water movement, infiltration and retention (Bottinelli et al., 2010; Hallaire and Curmi, 1994), hence the preservation of groundwater resources and the development of sustainable vegetation cover. This structure has been studied in a classical manner on "natural soils" to describe pedogenesis, as an indicator of the short- or long-term evolution of soils. It has also been studied by physical and indirect methods or micro-morphologically after a physical treatment (Watteau et al., 2012). In addition, this structure has also been studied to a certain extent for human-impacted soils, especially for constructed Technosols. However, it was demonstrated that in these soils, pedogenetic processes appear soon after soil construction (Séré et al., 2010). Porosity is one of the properties to be first affected in a new soil by pedogenetic factors such as climate, vegetation and soil fauna (Milleret et al., 2009). Porosity in a soil depends on several factors such as i) packing density, ii) breadth of the particle size distribution, iii) shape of particles and iv) cementing (Nimmo, 2004). But the main factors influencing porosity evolution in the early stages of natural soil formation are climate and biological activity, resulting for example in organic matter evolution, natural compaction, transfer of materials through erosion or illuviation (Falsone et al., 2012). Some modeling works on the genesis of natural soils show the importance of bioturbation on the factors of soil evolution (Finke and Hutson, 2008). There are few references concerning the evolution of porosity in the early pedogenesis of Technosol. For example Scalenghe and Ferraris (2009) show that in a new constructed Technosol the impact of biological factors will make it possible to create a new category of voids when finer particles start aggregating. This could lead to an increase or decrease in total porosity according to the kind and intensity of biological factors. For example, plants like *Medicago sativa*, due to their large roots, contribute to increasing the soil macroporosity (Caron et al., 1996). The presence of earthworms in a soil is reported to be beneficial in structuring

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soil, because they improve soil porosity (Bottinelli et al., 2010; Lavelle, 1988; Peres et al., 1998). However, other species of earthworms have a negative impact on soil porosity because they contribute to compacting it (Barros et al., 2001). Pores in soil are classified according to their water holding capacity. For example pores with equivalent diameters ranging from 0.5 to 50 μm (also known as storage pores) are reported to fulfill the function of a water reservoir for plants and microorganisms (Greenland and Pereira, 1977). Pores ranging from 50 to 500 μm are called "transmission pores" and are involved both in soil–water–plant relationships and in maintaining good soil structure conditions (Pagliai et al., 2004). The soils used for this work are Technosols constructed using urban and/or industrial wastes: thermally Treated Industrial Soil (TIS) (with a consequence on its composition, especially its organic matter content), Green Waste Compost (GWC) and paper-mill sludge (PS). Then, a soil construction process was conducted at the experimental station of the French Research Center for Soil Pollution and Remediation (Groupement d'Intérêt Scientifique sur les Friches Industrielles, GISFI, www.gisfi.fr) (Séré et al., 2008). The aim of this work is to develop a protocol for soil thin section image analysis, based on existing algorithms (Coster and Chermant, 1989; Noesis, 2008), to quantify porosity parameters in constructed Technosols and to study the evolution of pore system architecture during the early stages of pedogenesis. The implications that the architecture of soil pore system could have on the capacity of these constructed Technosols to carry out their basic functions (water holding capacity, water buffer/filter) are discussed. Among different quantified porosity parameters, we will choose those that indicate the evolution of pore structure according to time and soil construction modalities. We hypothesis that two different soil construction processes lead to contrasted porosity in the upper horizon of the constructed soils.

2. Materials and methods

2.1. Soil sampling

Soil samples were collected at the experimental station of the French Research Center for Soil Pollution and Remediation (Homécourt, North-Eastern France), where a process of soil construction has been performed on a 1 ha plot. The climate is continental with a mean rainfall of 760 mm/year and a mean temperature of 10 °C (extreme values: 22 °C to +37 °C). The pedological engineering process used for soil construction has been described by Séré et al. (2008). The constructed soil studied was a Spolic Garbic Hydric Technosol (Calcaric) (IUSS Working Group WRB, 2006; Séré et al., 2010). It was made of three technogenic parent materials. Green-Waste Compost (GWC), paper-mill sludge (PS), and thermally-Treated Industrial Soil (TIS) were stacked into layers forming three initially distinct horizons. From bottom to top there were: 45 cm of PS, 125 cm of TIS + PS mixture (2/3; 1/3 volumetric ratio), and 15 cm of GWC. Two different treatments were applied to the bottom of the profile: 1) "Water buffer" (Wb) with a layer of pure PS and 2) "Containment" (Co) with a layer of limed and compacted pure PS. PS, TIS and GWC are commercial names and the scientific objectives of the two treatments focused on water management and quality preservation. The experimental plot is divided in 24 mini-plots of 20 × 20 m of which there are13 Wb modality and 11 Co modality mini-plots (Fig. 1). Soil sampling was done on 04/11/2008 (T0) and 04/04/2010 (T2). Disturbed samples collected each year at different points of the mini-plot show that the soil heterogeneity is not enough to make a difference between them (Jangorzo, 2013). Twenty-three undisturbed soil cores were sampled in Kubiena boxes (9 × 6 cm) at the interface of TIS and GWC after removing the GWC layer. One thin soil section (20 μm thick, 9 × 6 cm) is realized from each sample according to the protocol developed by Guilloré (1980) and Murphy (1986). For that, the soil samples were dried by replacing water by acetone. Then they were impregnated under vacuum with polyester resin. The consolidated bloc is cut in two equivalent parts. One part is fixed on a thin glass with the same size (9 × 6 cm) and sliced until having a soil section of 20 μm.

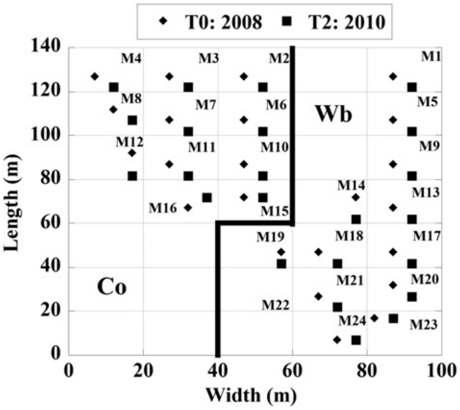

Fig. 1. Sampling design of the 1 ha of constructed soil plot (soil construction modalities: "Water buffer" (Wb) and "Containment" (Co). M: mini-plot (20 × 20 m).

2.2. Image acquisition

Images with a resolution of 1200 dpi (the minimum size of a pixel is 21.67 μm) of these thin sections were generated using a flatbed scanner (EPSON V750 Perfection Pro). In order maintain identical conditions, thin sections sampled in 2008 and 2010 were scanned successively. Each scan took around 3 min. The scanners were equipped with double lens, thereby guaranteeing homogeneous light distribution throughout the scanning process. Each thin section was scanned separately and the image was saved in TIFF-format. A subsample of 35.06 × 60.06 mm (2105.70 mm^2) was selected in order to have a common frame for all images. This sampling was done to avoid edge artifacts, as within this frame, results are known to be without bias (Coster and Chermant, 2001). With these scanned images, we quantified the >50 μm macroporosity (equivalent diameters exceeding 50 μm) to avoid one pixel pores.

Microporosity is known to play a significant role in the water reservoir later restituted to plants and microorganisms (Greenland and Pereira, 1977). To quantify this porosity (0.5–50 μm), we used magnified images generated from the above-mentioned thin sections. For this, we used a photonic Leica DM2500 microscope equipped with a Leica EC3 camera. We used 10 2008 thin sections and 10 others from 2010. Three images were captured on each thin section at a magnification of ×20, with a spectral resolution of 24 bits per pixel (true color). The minimum size of a pixel is 0.16 μm and each image had a size of 2048 × 1536 pixels, which is equivalent to 327.68 × 245.76 μm. We derived the <50 μm pores from magnified images and we fixed the limit of quantified micropores to >0.5 μm to avoid one pixel pores.

To be sure that the images were generated under identical conditions and were therefore comparable, we selected four thin sections from 2008 and four others from 2010. Each section was scanned three times. We built three spectral profiles, using Visilog 7, of a given feature (wood, stone, paper sludge) on each image. The spectral profile gives the intensity of red, green, and blue (RGB) bands of an object in an image. Then, the mean and standard deviation of intensities were calculated and compared. The aim of this step was to see if the distribution of RGB intensities of a soil feature varies depending on the number of scans *i.e.* if the color distribution is homogeneous. Results show that the intensity of RGB channels of a soil feature did not vary significantly when thin sections were scanned. If we analyze the variation of RGB channels from scan to scan, we find that the intensity of R channel is always quite higher than the G and B channels. The standard deviation of R, G and B channel intensities from scan to scan varies from 0 to 0.58, from 0 to 1 and from 0 to 0.58 respectively. However, we could conclude that the color distribution is the same for all thin sections scanned. Therefore, all images generated by the scanner can be considered to be comparable. When an image is generated, captor-inherent noise is undeniably introduced (Ledru et al., 2009). The intensity of noises