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Interactions between organisms and parent materials of a constructed Technosol shape its hydrostructural properties

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Abstract. There is no information on how organisms influence hydrostructural properties of constructed Technosols and how such influence will be affected by the parent-material composition factor. In a laboratory experiment, parent materials, which were excavated deep horizons of soils and green waste compost (GWC), were mixed at six levels of GWC (from 0 to 50 %). Each mixture was set up in the presence/absence of plants and/or earthworms, in a full factorial design ($n = 96$). After 21 weeks, hydrostructural properties of constructed Technosols were characterized by soil shrinkage curves. Organisms explained the variance of hydrostructural characteristics (19 %) a little better than parent-material composition (14 %). The interaction between the effects of organisms and parent-material composition explained the variance far better (39 %) than each single factor. To summarize, compost and plants played a positive role in increasing available water in macropores and micropores; plants were extending the positive effect of compost up to 40 and 50 % GWC. Earthworms affected the void ratio for mixtures from 0 to 30 % GWC and available water in micropores, but not in macropores. Earthworms also acted synergistically with plants by increasing their root biomass, resulting in positive effects on available water in macropores. Organisms and their interaction with parent materials positively affected the hydrostructural properties of constructed Technosols, with potential positive consequences on resistance to drought or compaction. Considering organisms when creating Technosols could be a promising approach to improve their fertility.

1 Introduction

Pedogenesis results from the dynamic interaction between climate, parent rock, and organisms. The most important factor(s) has been debated for a long time (Wilkinson et al., 2009) and studied independently (Jenny, 1941), but their interactions remain little understood (Paton, 1978; Amundson et al., 2007). Understanding of the influence of bioturbation (physical displacement by organisms) is not straightforward on soil formation (Amundson et al., 2007; Wilkinson et al., 2009). Some authors consider biotic mixing agents as a secondary cause of soil formation (Carson and Kirkby, 1972), while others argue that bioturbation plays a major role in forming soil (Paton 1978; Wilkinson and Humphreys, 2005).

Soils developed on non-traditional substrates and largely influenced by human activity are now referenced as Technosols in the World Reference Base for Soil Resources. When technogenic materials or artifacts are assembled deliberately to create soils, they are referred to as constructed Technosols (IUSS Working Group WRB, 2015). Many urban planners and green space enterprises are interested in constructed Technosols because these materials could be used as an alternative to topsoil material uptake from the countryside and the damage implied on the collecting site which need 10 000 years at least for reconstruction. Also, transportation costs and downsides could be avoided. Moreover, Technosols offer an opportunity to recycle urban waste, such as excavated deep horizons/backfills from enterprises of the building sector, sewage sludge from waste water plants, or green waste from greens pace enterprises or local authorities. In this regard, Technosols offer another life to these materials, which accumulation is urgent to cope with, due to health and environmental problems (Nemerow, 2009; Marshall and Farahbakhsh, 2013), while they could be used to improve urban ecosystem services (Morel et al., 2014) and form a closed loop that reduces the impact of cities on the environment. Constructed Technosols are different from other soils because they are designed assemblages of technogenic materials. Thus, the evolution of Technosols is different compared to the pedogenesis of natural soils (soils that generally show genetic relationships between the horizons they are composed of, and in which transitions among soils' types are visible. Humanity does not influence their formation process; Lehmann and Stahr, 2007). However, Technosols exhibit some formation processes similar to those observed in natural soil pedogenesis, such as decarbonization and aggregation (Séré et al., 2010; Jangorzo et al., 2014).

The pedogenesis of a constructed Technosol is particularly interesting. It begins with the mixing of parent materials in a proportion chosen by the experimenter, whereas the initial state of natural soils is never under the control of researchers.

Parent materials strongly influence the type of soil formed (Charman and Murphy, 2000). Organo-mineral composition of constructed Technosols determines several soil chemical and physical properties (pH, cationic exchange capacity, texture, etc.) and affects their quality (Molineux et al., 2009; Olszewski et al., 2010; Arocena et al., 2010; Rokia et al., 2014). The Influence of organic matter and texture on compactability of Technosols (Paradelo and Barral, 2013) and the formation of the organo-mineral complex in newly formed soil (Monserie et al., 2009) have also been documented. However, hydrostructural properties have not yet been investigated. This is of particular importance since constructed Technosols are often influenced by compaction (Jangorzo et al., 2013). Moreover, they are expected to provide water regulation services and to supply vegetation requirements. Therefore, we were interested in determining influences of different functional groups of organisms on soil hydrostructural properties. We focused on two kinds of organisms with different impacts on soil physical structure. Earthworms make an important contribution to soil function by influencing chemical, biological, and physical soil processes (Lavelle and Spain, 2001; Edwards, 2004), with consequences for ecosystem services (Blouin et al., 2013). Their major physical contributions are due to their high consumption rates and burrowing activity that affect soil structure, aggregation, and aeration (Blanchart et al., 1997), which influence the hydric properties of soil (Schrader and Zhang, 1997; Shipitalo and Butt, 1999). These modifications of hydrostructural properties by earthworms have tremendous consequences for plant growth (Scheu, 2003; Eisenhauer et al., 2007; Van Groenigen et al., 2014). Plant roots and rhizosphere inhabitants (microorganismes) also have a significant influence on aggregates and their stability (Jastrow et al., 1998; Rillig et al., 2002), sometimes more significant than that of earthworms (Blanchart et al., 2004). Roots penetrate the soil and create macropores which guarantee the exchange of gases in the vadose zone (Beven and Germann, 1982). Roots also create weak zones that fragment the soil and form aggregates, whose formation is strengthened by wetting–drying cycles due to water uptake by the plant (Angers and Caron, 1998). In addition, plant root residues provide a food source for microorganisms and fauna, which contribute to soil structure formation and stabilization (Innes et al., 2004). In return, microorganism-mediated changes in soil structure affect plant growth, mostly by modifying the root's physical environment (Dorioz et al., 1993).

In this study, we were interested in the effect of two soil-forming factors, i.e., parent materials and organisms, on hydrostructural parameters via measurements of soil shrinkage curves (SSCs) which represents the concomitant decrease in soil volume and water mass during drying (Haines, 1923). The influence of parent-material properties (especially clay content and type) (Boivin et al., 2004), organic matter (Boivin et al., 2009), and organisms (Kohler-Milleret et al., 2013; Milleret et al., 2009) on shrinkage properties has already been studied in natural soils. This study addresses the question of material–organism interaction on the hydrostructural properties of a constructed Technosols in a 5-month microcosm experiment with four "organism" treatments (control, plants, earthworms, plants + earthworms) combined with six percentages of green waste compost/excavated deep horizons under controlled climatic conditions.

2 Materials and methods

2.1 Parent materials

The mineral material excavated from deep horizons of soil (EDH) used in this study was provided by the ECT Company (Villeneuve sous Dammartin, France). This material is typically what is found when foundations are dug in the Île-de-France. It is mainly the result of the weathering of carbonated rock fragments of the Parisian Basin (France) from the Eocene. For our study, we collected 500 kg of EDH at eight locations from the base of ECT's landfill site, in order to have a composite sample representative of what may be used to construct Technosols around Paris. EDH is classified as carbonated sandy soil (Nachtergaele, 2001). Our material was composed of 880 $g\,kg^{-1}$ sand, 100 $g\,kg^{-1}$ silt, and 20 $g\,kg^{-1}$ clay after carbonate (lime) removal, which represents 431 $g\,kg^{-1}$ (W/W) of total dry mass. Without carbonate removal, EDH was composed of 110 $g\,kg^{-1}$ particles $< 2\,\mu m$ in size, 300 $g\,kg^{-1}$ particles from 2–50 µm, and 590 $g\,kg^{-1}$

Table 1. Mean ± 1 SE ($n=4$), main agronomic properties of technogenic materials used to make the constructed Technosols. EDH: excavated deep soil horizons; GWC: green waste compost.

Property	EDH	GWC
pH_{H_2O}	8.3 ± 0.0	7.9 ± 0.1
pHKCL	8.1 ± 0.1	7.5 ± 0.1
Organic carbon ($g\,kg^{-1}$)	0.38 ± 0.0	210.41 ± 4.2
Total nitrogen ($g\,kg^{-1}$)	0.03 ± 0.0	1.47 ± 0.0
Particle density ($g\,cm^{-3}$)	2.75 ± 0.2	2.06 ± 0.1
Bulk density ($g\,cm^{-3}$)	1.33 ± 0.0	0.61 ± 0.0
The residual moisture content after air drying ($g\,kg^{-1}$)	65.8 ± 4.0	87.9 ± 2.3

particles from 50 µm to 2 mm. X-ray diffraction performed with a Siemens D500 diffractometer (Cu-Ka, 40 kV, 30 mA) identified quartz, calcite, and dolomite as major minerals. The concentrations of organic carbon and nitrogen were measured by elemental analysis (Elementar Vario EL III). The green waste compost (GWC) used in our experiment was composed of cuttings from urban areas. Table 1 shows the main agronomic properties of EDH and GWC.

2.2 Experimental design and conditions

EDH and GWC were mixed using a concrete mixer to prepare six different mixtures with specific volumetric percentages of GWC at 0, 10, 20, 30, 40, and 50 %. One liter of each mixture was placed in a microcosm of $13 \times 13 \times 12.5$ cm with maximum capacity of 1.2 L. Water retention capacity of each mixture was measured at the beginning of the experiment by using a pressure plate apparatus (Richards, 1948) with a water potential of -31 kPa. During the experiment, microcosms were moistened two to three times a week with deionized water to maintain soil moisture at 80 % of field capacity for each mixture (Table S1 in the Supplement).

Plants were sown 24 h after watering the pots; and earthworms were introduced 24 h after sowing. Each percentage of GWC was combined with four treatments: a control without organisms (C), a treatment with two individuals (0.5 ± 0.1 g each) of the endogenic earthworm species *Aporrectodea caliginosa* (E), a treatment with *Lolium perenne* plants (50 seeds with a 80 % germination rate scattered homogeneously on the microcosm surface) (P), and a treatment with both earthworms and plants (EP). In total, 96 microcosms were divided into 24 treatments, each with four replicates.

Microcosms were kept 21 weeks in a climate chamber (S10H, Conviron, Canada) under the following conditions: photoperiod of 12 h, luminosity of 500 ± 20 µmol photons $m^{-2}\,s^{-1}$; temperature at 22 and 20 ± 0.2 °C during the day and at night, respectively; and 75 ± 2 % air humidity.

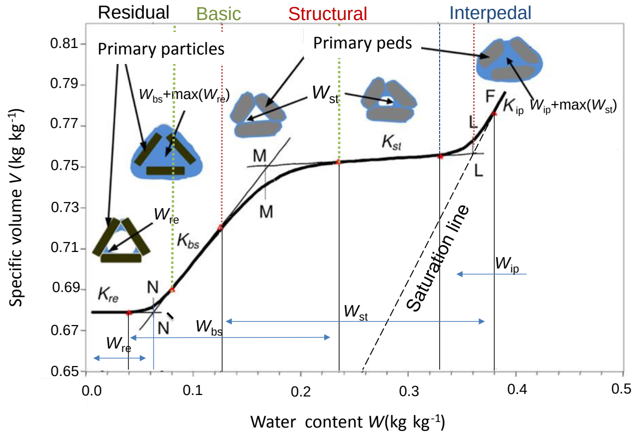

Figure 1. Configurations of water partitioning in macropores and micropores related to the shrinkage phases of a standard shrinkage curve (water content W, specific volume V). (Adapted from Braudeau et al., 2004.)

2.3 Shrinkage analysis

Technosol samples were collected from the surface of each microcosm at the end of the experiment using a 5 cm high, 5 cm diameter cylinder and were placed on a wet porous plate for saturation with deionized water according to the manual instructions of Eijkelkamp (referee) for 7 days by applying a water potential of 0 kPa at the base of the sample. The shrinkage curve was continuously measured according to Braudeau et al. (1999) by using the RETRACTOMETER© apparatus. Water-saturated Technosol samples were placed in an oven at a constant temperature (30 °C) to provide continuous and rapid evaporation. An electronic scale (0.01 g precision) ensured accurate measurement of water loss during drying. Each sample's volume (diameter, height) was determined with laser beams and recorded along with its mass every 10 min.

At the end of the measurement, samples were dried in an oven at 105 °C for 48 h to measure dry mass and bulk density. These data were converted into soil specific volume (V, $cm^3_{soil}\,g^{-1}_{dry\,soil}$) and water content ($W$, $g_{water}\,g^{-1}_{soil}$). We then determined the SSC to describe hydrostructural properties, as proposed by Assi et al. (2014). The data obtained by shrinkage measures were fitted according to the pedostructure model (Braudeau et al., 2004). In this model, the SSC is subdivided into a maximum of four shrinkage phases (interpedal/saturated (ip), structural (st), basic (bs), and residual (re) shrinkage phases) due to the four types of water (W_{ip}, W_{st}, W_{bs}, W_{re}) (Fig. 1). The pedostructure is considered an assembly of primary peds (aggregates formed by clay particles) that determines two nested levels of organization: the macropore level (containing $W_{ma} = W_{ip} + W_{st}$) and the micropore level (containing $W_{mi} = W_{re} + W_{bs}$). These levels do not refer to pore size by itself but to water pore behavior during soil drying. Based on this distinction, the two pore systems were called plasma (micropores) and structural properties (macropores) (Boivin et al., 2004; Schaffer et al., 2008).

The three transition points separating the four pseudo linear shrinkage phases (Fig. 1) are points L, M, and N, which are at the intersection of the tangent straight lines of the linear phases. According to this model of SSC (Braudeau et al., 1999, 2004), the value of the water content at each point is equal to the value of max (W_{st}) for W_L, max $(W_{mi}) = \max(W_{re}) + \max(W_{bs})$ for W_M, and max (W_{re}) for W_N. The other hydrostructural parameters are slope of the saturated phase (K_{ip}); slope of the structural phase (K_{st}); slope of the basic shrinkage phase (K_{bs}), slope of the residual phase (K_{re}); and three parameters (K_L, K_M, and K_N) related to the SSC shape at points L, M, and N, respectively. Finally, according to Braudeau et al. (2001),

$$\mathrm{Max}(W_{re}) = W_N, \tag{1}$$

$$\mathrm{Max}(W_{bs}) = W_M - W_N, \tag{2}$$

$$\mathrm{Max}(W_{st}) = W_L - W_M. \tag{3}$$

Specific volume V as a function of the water content W obtained from the Braudeau model was converted into a void ratio (e, $\mathrm{cm^3_{pore}\,cm^{-3}_{solid}}$) as a function of the moisture ratio (ν, $\mathrm{cm^3_{water}\,cm^{-3}_{solid}}$). This step makes it easier to compare Technosols that have different compositions and thus different particle densities. Consider Eqs. (4) and (5):

$$\nu = (\rho_s/\rho_w)\,W, \tag{4}$$

$$e = V\rho s - 1, \tag{5}$$

with ρ_w being the water density and ρ_s the particle density ($\mathrm{g\,cm^{-3}}$) calculated for all mixtures from measurements of GWC and EDH using a pycnometer on materials sieved at 2 mm (ISO 17892-3:2004).

All hydrostructural parameters were transformed with Eqs. (4) and (5) and thus became the moisture ratio at macropore saturation (ν_L), the moisture ratio at micropore saturation (ν_M), the moisture ratio at the shrinkage limit (ν_N), the four slopes (K_L, K_{st}, K_{bs}, K_{re}), parameters related to the SSC shape (K_L, K_M, K_N), and the void ratio at the end of the shrinkage period (e_0).

Considering these hydrostructural parameters (Braudeau et al., 2004), the ratio of the maximum available water for plants from macropores (ν_{ma}, $\mathrm{cm^3_{water}\,cm^{-3}_{solid}}$) and the ratio of the maximum available water for plants from micropores (ν_{mi}, $\mathrm{cm^3_{water}\,cm^{-3}_{solid}}$) can be calculated from Eqs. (2) and (3) as follows:

$$\nu_{ma} = \nu_L - \nu_M, \tag{6}$$

$$\nu_{mi} = \nu_M - \nu_N. \tag{7}$$

The sum of both is the total moisture ratio (ν_{Total} in $\mathrm{cm^3_{water}\,cm^{-3}_{solid}}$). Finally, volumetric water content (Θ, $\mathrm{cm^3_{water}\,cm^3_{soil}}$) was calculated to compare available water reservoirs (holding capacities) for plants:

$$\Theta = \nu \cdot (\rho_d/\rho_s) = \nu \cdot (\rho_d/\rho_s) \tag{8}$$

with ρ_d being the bulk density ($\mathrm{g_{solid}\,cm^{-3}_{soil}}$). Similarly, we calculated the volumetric water content from macropores (θ_{ma}) and micropores (θ_{mi}), by applying the following equations:

$$\theta_{ma} = \theta_L - \theta_M, \tag{9}$$

$$\theta_{mi} = \theta_M - \theta_N. \tag{10}$$

Eventually the sum of both is known as the total volumetric water content for plants (θ_{Total}).

2.4 Plant harvest and root size distribution

Plants were cut at the soil surface 21 weeks after sowing. Fresh leaves were weighed, dried in an oven at 50 °C for 2 days, and weighed again. Root mass was estimated from one quarter of the pot, since other quarters were used for physicochemical and shrinkage analyses, requiring non-disturbed soil physical properties (i.e., root or earthworm sampling).

Dry root biomass distribution among diameter classes was determined according to the method of Blouin et al. (2007). It is based on the granulometry method used to assess soil texture: roots are dried, cut transversely with a mixer, and placed on a column of sieves with decreasing mesh size. During the shaking of the sieve column, root fragments with a section diameter smaller than the mesh size pass through this mesh and stop on the first sieve with a mesh size below that of the root section diameter. Biomass distribution is assessed by weighing the biomass recovered in each sieve. Five diameter classes were chosen according to sieve mesh size: 0–100, 100–200, 200–400, 400–800, and > 800 µm.

2.5 Data analysis

We calculated means and standard errors of hydrostructural parameters for all treatments by fitting the curves with the hydrostructural model (Table S2). The hydrostructural parameter representing the slope of the interpedal K_{ip} phase, the k_M parameter related to the shape of the soil shrinkage curves, and K_{re} the slope of the residual phase were not included, since they were constants for all mixtures ($K_{ip} = 1$), ($K_M = -53$), and ($K_{re} = 0$). Statistical analyses were performed with the R 3.0.3 software (R Core Team, 2014). To assess the correlation of each factor's influence on the variance of the eight hydrostructural parameters, redundancy analysis (RDA) was performed with the vegan package (Jari Oksanen et al., 2013). Then partial RDA was performed to decompose the variation of hydrostructural metrics according to the combination of GWC, organisms, and their interaction. Differences between treatments were tested with Tukey's honest significance test. To identify which hydrostructural variables separated the treatments, the MASS and ade4 packages were used for principal component analysis (PCA) (Venables and Ripley, 2002) and for linear discriminant analysis (LDA) (Dray and Dufour, 2007). Treatment

Table 2. Two-way ANOVA showing the effects of the presence/absence of earthworms (E) and the proportion of green waste compost (GWC) in the mixtures on plant dry biomasses, shoot : root ratio, and root system structure (thick root ≥ 400 µm and fine root < 400 µm) ($n = 48$) (d.f. is degrees of freedom).

	d.f.	Aboveground biomass (g)	Belowground biomass (g)	Total biomass (g)	Shoot : root ratio	Thick root proportion	Fine root proportion
Complete model	11	11.29***	5.85***	13.33***	1.27^{ns}	0.78^{ns}	0.95^{ns}
GWC	5	10.27***	8.73***	16.22***	2.08^{ns}	0.49^{ns}	0.72^{ns}
E	1	65.65***	15.24***	60.12***	0.14^{ns}	0.62^{ns}	1.59^{ns}
GWC · E	5	1.43^{ns}	1.08^{ns}	0.39^{ns}	0.68^{ns}	0.56^{ns}	1.05^{ns}

The number in the table are the F values; significance codes: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$, ^{ns} $P > 0.05$.

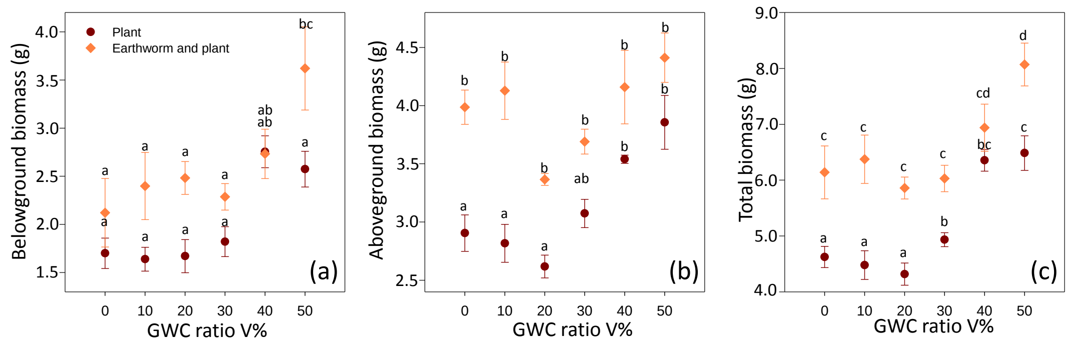

Figure 2. (a) Belowground, **(b)** aboveground and **(c)** total biomass production of *Lolium perenne* according to different ratios of green waste compost in the presence/absence of the earthworm *Aporrectodea caliginosa*; mean ± SE, $n = 4$ per treatment. Tukey test, significant differences are indicated by different letters, $P < 0.05$.

separation based on hydrostructural variables was tested with Wilks and Pillai tests. The influences of the presence/absence of earthworms and the percentage of GWC were assessed with two-way or three-way ANOVA with GWC, earthworms, and plants taken separately. Independent variables were considered to have an influence on dependent variables when the probability value was < 0.05.

3 Results

3.1 Plant growth and development

Belowground biomass ranged from 1.7 to 3.6 g and aboveground biomass from 2.9 to 4.4 g, which amounted to a total biomass of 4.6 to 8.1 g (Fig. 2). Two-way ANOVA showed that both GWC percentage and the presence of earthworms had a positive effect on dry belowground, aboveground, and total biomasses (Table 2). GWC percentage had almost no influence from 0 to 30 % on total biomass but increases plant production at 40 and 50 % (Fig. 2a–c). Earthworm presence had a positive effect on belowground biomass only at 50 % GWC, whereas aboveground biomass was affected only in the 0–30 % GWC range. As a result total biomass was always significantly higher in the presence of earthworms, except at 40 % GWC. On average, earthworms increased total plant biomass of 21 % (Fig. 2c). The best treatment for plant growth was clearly the mixture of 50 % GWC with earthworms, with a total dried plant biomass of 8.1 g, which was significantly higher than all other mixtures, except for 40 % GWC with earthworms. There was no interaction between the effects of GWC percentage and earthworms on plant biomasses, which means that these two effects are additive. All parameters describing biomass allocation inside the plant, such as the root : shoot ratio and the thick (≥ 400 µm) and fine (< 400 µm) root percentages, were not affected by the presence of GWC percentage, earthworms, or their interaction (Table 2); we thus concluded that GWC percentage and presence of earthworms had a quantitative influence but not a qualitative one, as growth was affected but not development.

3.2 Specific influence of organisms and parent materials on the hydrostructural parameters

All our Technosols exhibited the classical sigmoid shape of the shrinkage curve reported for most natural soils (Laurizen, 1948; Braudeau et al., 1999; Peng and Horn, 2005) (Figs. 3 and 4); thus, shrinkage phases (residual, basic, structural, and the saturating shrinkage phase) were easy to recognize. All the parameters deduced from SSC are given in Table S2.

High GWC percentage caused moisture ratio ν and void ratio e to increase (Fig. 3). The positive effect of GWC percentage was particularly important in treatments with plants at 50 % GWC (Fig. 3c) and in treatment with earthworms and plants at 40 and 50 % (Fig. 3d). Earthworms showed a positive influence on the void ratio in the 0–30 % GWC range, but this positive effect disappeared at 40 and 50 % GWC (Fig. 4). The influence of plants on void ratio was positive for 10, 20, 30, and 50 % GWC but not at 0 and 40 % GWC (Fig. 4). The simultaneous presence of plants and earthworms resulted in a positive effect on void ratio for all mixtures (Fig. 4). For example e_0 varied in the range of 0.9–1.4, 1.0–1.4, 0.9–1.6, and 1.2–1.9 $cm^3\ cm^{-3}$ for control, earthworms, plants, and plants and earthworms, respectively (Fig. 4). This corresponded to an increase of 59 % in the presence of plants, 42 % in the presence of earthworms, and 77 % in the presence of both plants and earthworms as compared with the control, for the void ratio at macropore saturation (ν_L) in the 50 % GWC mixture. The moisture ratio was also positively affected by the GWC percentage; for example when we compared moisture ratio at macropore saturation we noticed an increase of 59 % between treatments 0 and 50 % GWC in the control without organisms (Fig. 3a). SSC revealed that the presence of organisms had a somewhat similar effect on hydrophysical properties of Technosols to GWC percentage: for example, the aspect of shrinkage curves when GWC was 0 % in the presence of earthworms and plants seemed like the control treatment at 30 % GWC (Fig. 4): e_0 ($e_0 = 1.1$) and total moisture ratio ($\approx 1\ cm^3\ cm^{-3}$) (Table S2). The slopes in the structural phase (K_{st}) were steeper in the presence of plants. We noticed that the structural phase in the presence of earthworms reveals itself to be shorter for 40 and 50 % GWC than in the 0–30 % GWC range (Fig. 4).

RDA performed on eight hydrostructural parameters of the Table S2 showed that the factors "GWC percentage" and "organisms" had an influence on hydrostructural parameters. The total percentage of variance explained by these factors was high: 72 % ($P = 0.005$). The influence of factors taken independently was not very high: the total percentage of variance explained by the GWC percentage, regardless of the organisms, was 14 % ($P = 0.005$), while the total percentage of variance explained by the organisms, regardless of the GWC percentage, was 19 % ($P = 0.005$). Taken together, the single factors accounted thus for 33 % of explained variance, whereas their interaction (organisms × GWC percentage effect, estimated from the subtraction of single factors' effects from total variance) was responsible for 39 % of the variance (72–33 %). This means that predicting variations in hydrostructural parameters of our Technosols requires taking into account variation in parent materials and organisms simultaneously.

The LDA explained 76 % of hydrostructural properties' observed variance ($P < 0.001$; Wilks and Pillai tests) (Fig. 5). Axis 1, which explained 42 % of the total variance, distinguished treatment "earthworms" from treatment "earthworms and plants", whereas axis 2, which explained 26 % of the total variance, separated the "control" and the "plants"

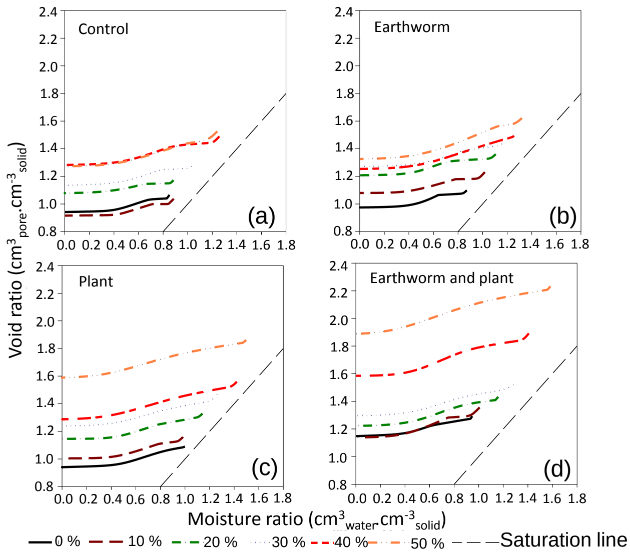

Figure 3. Averaged shrinkage curves ($n = 4$ per curve) for the six mixtures of GWC and excavated deep horizons (0, 10, 20, 30, 40, 50 % of GWC) reported as the void ratio as a function of the moisture ratio. Each panel represents one of the four treatments: **(a)** control, **(b)** earthworms, **(c)** plants, and **(d)** earthworms and plants. The dashed line represents the saturation line.

treatments. By relating the correlation circle (Fig. 5a) to the factorial plan (Fig. 5b) we found that (i) the parameter related to the shape of shrinkage curves between interpedal and structural phases (K_L) was higher for the control than for organism treatments; (ii) earthworms increased moisture ratio at the shrinkage limit (ν_N); (iii) plants increased the slope of the structural phase (K_{st}); and (iv) the simultaneous presence of plants and earthworms increased the moisture ratio at saturated macropores (ν_L), minimum void ratio (e_0), and a parameter related to the shape of shrinkage curves (K_N).

Additional PCAs were performed to characterize the effect of organisms on hydrostructural properties for each GWC percentage. The effect of plants was not significant at 0, 10, and 20 % GWC ($P > 0.05$, Monte Carlo test), while it was significant at 30, 40, and 50 % GWC ($P < 0.05$, Monte Carlo test). In contrast, combined influences of plants and earthworms were always significant ($P < 0.05$, Monte Carlo test).

3.3 Influence of organisms and parent materials on moisture ratio and available water for plants

The complete ANOVA model with GWC percentage, earthworms, and plants had a significant effect ($P < 0.001$) on micropore, macropore, and total moisture ratios and available volumetric water contents (Table 3). Considering single factors, increasing the GWC had a positive influence on micropore, macropore (GWC < 40 %) and total moisture ratios and available volumetric water contents ($P < 0.001$). Plants had an influence on all of the previous variables, ex-

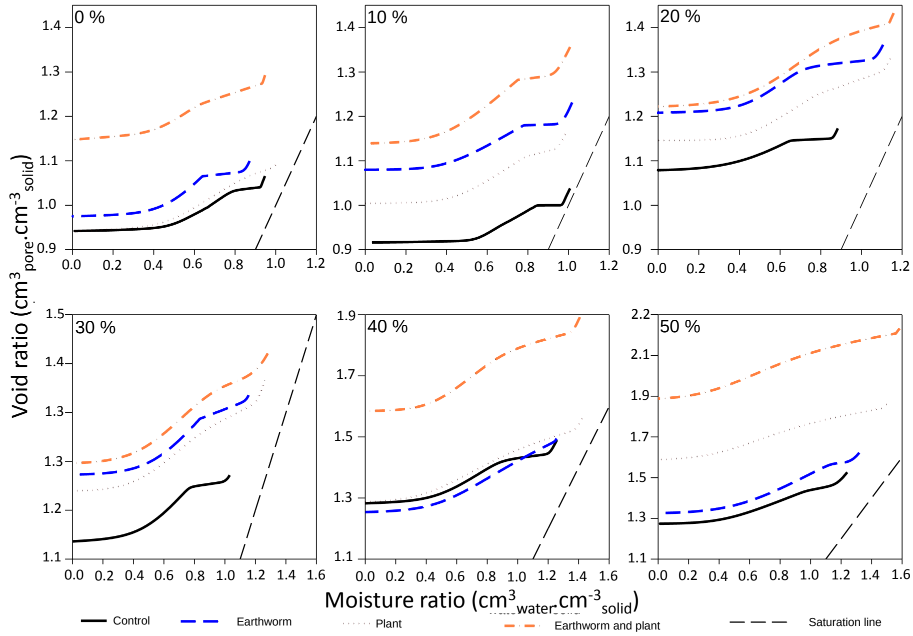

Figure 4. Averaged shrinkage curves ($n = 4$ per curve) for the four treatments (control, earthworms, plants, earthworms and plants) reported as the void ratio as a function of the moisture ratio. Each panel represents one mixture of GWC and excavated deep horizons: **(a)** 0 % GWC, **(b)** 10 % GWC, **(c)** 20 % GWC, **(d)** 30 % GWC, **(e)** 40 % GWC, **(f)** 50 % GWC. The dashed line represents the saturation line.

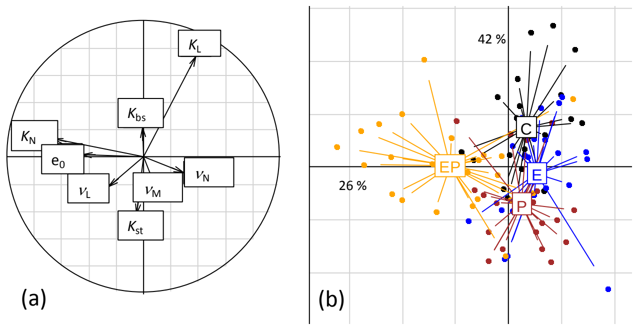

Figure 5. Linear discriminant analysis of the influence of control, earthworm, plant, and both earthworm and plant on hydrostructural parameters. The first and the second axes explained 42 and 26 % of the variance, respectively. ν_L: moisture ratio at saturated macropores; ν_M: moisture ratio at saturated micropores; ν_N: limit of shrinkage; e_0: void ratio at the end of the shrinkage curve; K_{st}: the slope of structural phase; K_{bs}: the slope of the basic phase; and K_L, K_N: parameters related to shape form.

cept for micropore volumetric available water content. Earthworms affected micropore and total moisture ratios but not the macropores moisture ratio; they affected micropore volumetric available water content (Table 3).

The presence of earthworms influenced the effect of GWC percentage on moisture ratio and total volumetric available water contents at macropore and micropore. For example, in the absence of earthworms, GWC percentage had a positive influence on moisture ratio at macropore for 0–40 % GWC, while in the presence of earthworms, moisture ratio at macropore decreased at percentages of 30–50 %. The presence of plants modified the influence of GWC percentage on moisture ratios at micropore and macropore, and total volumetric available water at macropore and micropore. For example, in the absence of plants, the influence of GWC percentage on moisture ratio at macropore was positive at percentages of 0–40 % and became negative at 50 %, whereas in the presence of plants, the influence of GWC was positive regardless of its percentage (Fig. 4a). A similar influence was observed for the interaction between plants and GWC percentage on macropore volumetric available water (Fig. 6d). The interaction between earthworms and plants had a significant effect only for moisture ratios in micropore and macropore but not for total moisture ratio, suggesting an opposite effect on micropores and macropores (Table 3). Indeed, ν_{ma} was higher in the plants and earthworms treatment as compared with the plant treatment and the earthworm treatment, but ν_{mi} was higher in the earthworm treatment or the plant treatment as compared with the plants and earthworms treatment. The triple interaction had a significant influence on moisture ratio and volumetric available water at macropore (Table 3). For example, in the absence of plants, earthworms amplified the negative influence of high GWC percentages on moisture ratio at macropore, whereas in the presence of plants, earthworms amplified the positive influence of plants at high GWC percentages, giving a maximum moisture ratio at macropore and total volumetric available water (Fig. 6a and d).

Table 3. Three-way ANOVA testing the effect of GWC, earthworms (E), and plants (P) on the maximum moisture ratio from macropores (ν_{ma} cm^3_{water} cm^{-3}_{solid}), maximum moisture from micropores (ν_{mi} cm^3_{water} cm^{-3}_{solid}), total moisture ratio (ν_{Total} cm^3_{water} cm^{-3}_{solid}), macro available water (θ_{ma} cm^3_{water} cm^{-3}_{soil}), micro available water (θ_{ma} cm^3_{water} cm^{-3}_{soil}), and finally total available water (θ_{Total} cm^3_{water} cm^{-3}_{soil}) ($n = 96$) (d.f. is degrees of freedom).

	d.f.	ν_{ma}	ν_{mi}	ν_{Total}	θ_{ma}	θ_{mi}	θ_{Total}
Complete model	23	13.68***	18.63***	34.91***	10.73***	26.77***	23.8***
GWC	5	34.35***	122.36***	124.30***	13.89***	103.01***	98.61***
P	1	66.16***	23.97***	43.06***	35.47***	0.07^{ns}	16.88***
E	1	0.42^{ns}	31.62***	19.59***	0.36^{ns}	4.26*	1.51^{ns}
P · E	1	5.63*	7.25**	1.88^{ns}	2.28^{ns}	3.09^{ns}	0.23^{ns}
GWC · P	5	27.64***	4.87***	1.46^{ns}	17.97***	16.16***	2.64*
GWC · E	5	3.55**	0.96^{ns}	1.78^{ns}	2.41*	2.02^{ns}	2.73*
GWC · P · E	5	11.47***	1.42^{ns}	1.26^{ns}	7.44***	0.45^{ns}	1.80^{ns}

The number in the table are the F values; significance codes: * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$, ^{ns} $P > 0.05$.

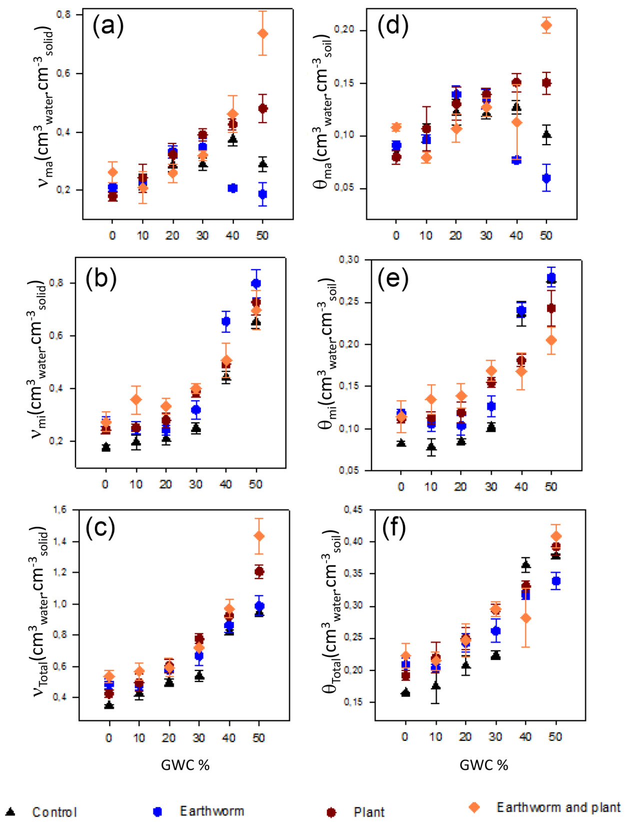

Figure 6. Moisture ratio at **(a)** maximum saturated macropores (ν_{ma} cm^3_{water} cm^{-3}_{solid}) and **(b)** maximum saturated micropores (ν_{mi} cm^3_{water} cm^{-3}_{solid}); **(c)** total moisture ratio (ν_{Total} cm^3_{water} cm^{-3}_{solid}); available water of **(d)** macropores (θ_{ma} cm^3_{water} cm^{-3}_{soil}) and **(e)** micropores (θ_{mi} cm^3_{water} cm^{-3}_{soil}); and **(f)** total available water (θ_{Total} cm^3_{water} cm^{-3}_{soil}) according to the proportion of compost for the four organism treatments (presence/absence of earthworms and/or plants). Mean ± SE, $n = 4$ per treatment.

3.4 Relation between total plant biomass and available water

Linear regressions between total plant biomass (g) and available volumetric water content (cm^3_{water} cm^{-3}_{soil}) were performed using earthworm presence or absence as a categorical independent variable (Fig. 7). Significant differences were found between total plant biomass with or without earthworms ($P < 0.001$), and plant biomass was higher with earthworms than without. In addition, total plant biomass increased with available water ($P < 0.001$). However the difference in slope of the two linear regressions (Fig. 6) was not significant ($P = 0.569$). The best equations summarizing the relation between total dried plant biomass (X, g) and plant-available water (θ_{Total}, cm^3_{water} cm^{-3}_{soil}) were $X = 8.97 \cdot \theta_{Total} + 4.07$ and $X = 8.97 \cdot \theta_{Total} + 2.69$ with and without earthworms, respectively ($P < 0.001$, adjusted $r^2 = 0.65$). Table S3 showed the results of both equations.

4 Discussion

Shrinkage analysis was initially developed to describe hydrostructural properties of natural soils (Haines, 1923; Milleret et al., 2009), and it was used by Kohler-Milleret et al. (2013) and Milleret et al. (2009) to evaluate the influence of organisms in natural soils. However, the effect of organisms on hydrostructural properties of constructed Technosols has never been studied before. Our study shows that shrinkage curve analysis was relevant for describing Technosol structure and water-holding capacities. In our case, parent materials exhibited highly divergent behaviors: EDH showed a SSC with the typical sigmoid shape that reveals two levels of organization (presence of both micropores and macropores). However, the green waste compost shrinkage curve had a hyperbola shape (Deeb et al., 2016). Thus, the behavior of the mixtures was difficult to predict. Here, we showed two embedded levels of organization in the mixtures, with a

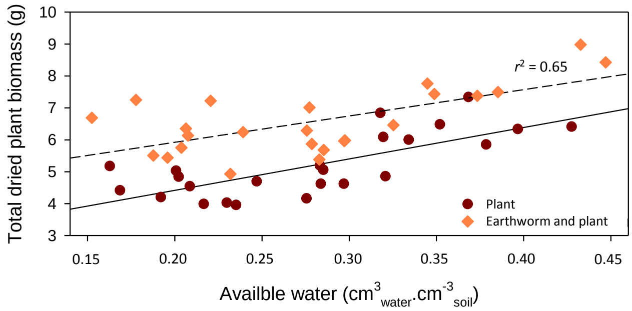

Figure 7. Linear regression between total dry plant biomass and available water (cm^3_{water} cm^{-3}_{soil}) with earthworm (dotted line) or without earthworm (plain line). Plant biomass was higher with earthworms than without ($P < 0.001$). Total plant biomass increased with available water, but the difference in slope of the two linear regressions was not significant. The best equations fitting the relation between total dried plant biomass (X, g) and plant available water (θ_{Total} cm^3_{water} cm^{-3}_{soil}) are $X = 8.97 \cdot \theta_{Total} + 4.07$ and $X = 8.97 \cdot \theta_{Total} + 2.69$ with and without earthworms, respectively ($P < 0.001$, adjusted $r^2 = 0.65$).

sigmoid shape even at the highest GWC percentage (50 %, V/V). Because this organization is often, but not always, observed in natural soils, we conclude that after 5 months mixtures of mineral and organic materials behave as many natural soils from a hydrostructural viewpoint.

4.1 Influence of green waste compost on hydrostructural properties

Shrinkage curve analysis indicated a positive correlation between the amount of GWC percentage and the quantity of macropores and micropores. This is likely due to organic matter present in the GWC: an increase in total void ratio was also observed in natural soil amended with organic matter (McCoy, 1998; Marinari et al., 2000; Tejada and Gonzalez, 2003) and recently in Technosols (Paradelo and Barral, 2013). The addition of GWC to EDH seems a promising strategy to obtain useful hydric properties that match plant needs for water and are similar to those observed in natural organic soils.

4.2 Influence of earthworm *Aporrectodea caliginosa* on hydrostructural properties

Earthworms were responsible for a significant increase in total moisture ratio (Fig. 5c). This was the result of an increase in moisture ratio at saturated micropore, not macropore (Fig. 5). Through this mechanism, earthworms are likely to have a positive impact in climates with occasional droughts. Earthworms might thus help plants to face a water deficit in drying Technosols and effectively contribute to water regulation. This result was surprising: earthworms are generally known to affect macroporosity through their galleries. Our results differed from those obtained with *Allolobophora chlorotica*, an endogenic earthworm that compacts the soil and was responsible for a decrease in porosity, measured by shrinkage curves (Milleret et al., 2009; Kohler-Milleret et al., 2013). These discrepancies between results could be due to the endogenic earthworm influences on hydrostructural properties that are species-specific, or to the parent materials used in the experiment. For example, when the percentage of GWC was > 30 %, the soil was also slightly compacted by earthworms. However, with GWC ratio ≤ 30 %, earthworms tend to increase void ratio (Fig. 4). The absence of an increase in macroporosity caused by earthworms could also be explained by a progressive compaction of the soil throughout the experiment, with a decrease in macroporosity, as is observed in Technosols (Jangorzo et al., 2013). This phenomenon could be particularly common with experimental Technosols made of sieved parent materials, which have never been subjected to previous shrinkage.

4.3 Influence of *Lolium perenne* on hydrostructural properties

The general influence of roots on soil structure was observed by Monroe and Kladivko (1987), Angers and Caron (1998), and Kautz et al. (2013). This positive effect is mainly due to plants' abilities to create macro-aggregates and macropores. Similar results have been reported in other studies (Reid and Goss, 1982; Caron et al., 1996). Moreover, the positive influence of plants on moisture ratio at macropore increased with the presence of earthworms. It was not due to the direct influence of earthworms, which improved moisture ratio at saturated micropore (ν_N and ν_M) but had a null influence on moisture ratio at saturated macropore. This synergistic effect between plants and earthworms was thus likely to be due to an increase of the plant influence in the presence of earthworms (Fig. 7). Indeed, earthworms were increasing plant root biomass (Fig. 2), and thus the positive effect of plant roots on hydrostructural properties was improved. This result emphasizes the importance of considering ecological interactions among functional groups such as plants and earthworms.

We also showed how plants and earthworms can help confront one of the main problems encountered by Technosols: compaction. Technosols often tend to compact with time (Jangorzo et al., 2013). Organisms such as plants or earthworms are responsible for maintaining a high volume of voids and moisture per solid-volume unit (void and moisture ratios, respectively). By introducing these organisms at the very beginning of Technosol creation, i.e., before compaction, managers could initiate a virtuous cycle in which organisms maintain loose soil structure. This favors the establishment of other organisms that maintain their own habitats, which in turn could benefit from plants and earthworms by preventing later compaction.

Because the influence of plants on hydrostructural properties was significant at 30–50 % GWC, one had to consider the initial composition of mixtures of materials to benefit from this organismal positive feedback.

4.4 Interactions between organisms and parent materials in Technosol pedogenesis

This study allows comparing the influence of the proportion of parent materials (0–50 % GWC) and the presence of organisms (presence/absence of plants and earthworms) on pedogenesis. These situations are far from covering all kinds of parent materials and organisms but are a first attempt to compare the relative importance of soil-forming factors under experimental conditions based on parent materials that never experienced the biological activity of macro-organisms such as plants and earthworms. We found that variations in Technosol hydrostructural properties were poorly explained by parent materials alone (14 % of explained variance) and by organisms alone (19 % of variance), whereas material–organism interaction explained more than the sum of their individual influences (39 % > 33 %). This complexity brought about by ecological interaction between organisms and their abiotic environment could partly explain the debate between those considering that organisms play a negligible role in pedogenesis (Jenny, 1941; Carson and Kirkby, 1972) versus those stressing their importance (Paton, 1978; Wilkinson and Humphreys, 2005). Indeed, if the influence of organisms is particularly important in interaction with parent materials, its observation may be random. Pedogenesis, particularly in the case of Technosol, appears as an internal disciplinary field of study that needs two ecological aspects. We found that biological activity improved Technosol properties by increasing aggregation, porosity, and water-retention capacity, with potential consequences on resistance to drought and erosion. An original research perspective could be to investigate benefits of these changes caused by plants and earthworms for their own survival and reproduction to determine if these biological activities increase the fitness of these organisms and could thus be considered as a niche construction (Odling-Smee et al., 1996).

5 Conclusions

In a nutshell, we found that compost and plants play a positive role in macroporosity and microporosity in Technosols, while earthworms affect only microporosity. GWC percentage positively affected macroporosity up to a percentage of 30 %, and plants were responsible for extending this positive influence at 40 and 50 % GWC. The simultaneous presence of earthworms and plants was responsible for a synergistic, positive influence on macroporosity. These observations highlighted the need to consider plants not only as an output indicating the level of fertility, but also as an actor in Technosol construction, like earthworms. Organisms that physically modify their environment by creating, destroying, or maintaining ecological niches have been called "ecosystem engineers" (Jones et al., 1994). These ecosystem engineers can help restore ecosystems (Byers et al., 2006) and create new ecosystems such as constructed Technosols by assisting managers, who could "subcontract" one aspect of management. Therefore, instead of increasing the amount of compost, which is usually expensive, managers could avoid the difficult-to-explain negative influence of high percentages of compost by favoring conservation, recolonization, or inoculation of ecosystem engineers such as plants and earthworms, especially in combination (Blouin et al., 2013).

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