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SUITMA 9: URBANIZATION — CHALLENGES AND OPPORTUNITIES FOR SOIL FUNCTIONS AND ECOSYSTEM SERVICES

Early colonization of constructed Technosols by macro-invertebrates

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Abstract

Purpose Anthropogenic activities lead to soil degradation and loss of biodiversity, but also contribute to the creation of novel ecosystems. Pedological engineering aims at constructing Technosols with wastes and by-products to reclaim derelict sites and to restore physico-chemical functions.

Materials and methods The biological (dynamics of soil and epigeic macroinvertebrate assemblages) and physical (chemical and physical fertility) properties have been studied in two constructed Technosols under grassland during 4 years after their implementation.

Results and discussion The soils exhibited a moderate chemical fertility (high organic matter and calcium carbonate contents, low nitrogen content) and a good physical fertility that only slightly evolved over the monitored period. Macro-invertebrates have colonized these soils. This colonization was characterized by an increasing number of individuals and species over time. The diversity and abundance values fell within those quoted in the literature for similar natural soils. Epigeic invertebrates presented a succession, indirectly linked to changes in soil parameters. No succession was recorded for soil invertebrates. However, the proportion of soil detritivores, an important functional group for soil evolution, grew consistently. Questions about soil invertebrates' functional complementarity/redundancy emerge in such artificially created ecosystem.

Conclusions The constructed Technosol, on which a meadow was sown and well-established after 4 years, can host numerous soil invertebrates. In addition, an increase in diversity was monitored throughout the duration of the study.

Keywords Brownfield management · Earthworms · Ground beetles · Spiders · Succession

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1 Introduction

Anthropogenic activities have a major impact on soil quality by degrading both physical and chemical characteristics (De Kimpe and Morel 2000), by contaminating the soils (Morel et al. 2005) and leading to massive loss of biodiversity. Widespread practice consists in replacing the degraded soil by natural topsoil materials from agricultural or forest areas to restore soil functions. Recently, in brownfield management, new in situ techniques such as pedological engineering have been developed to construct artificial soils, that are designed to fulfill physico-chemical functions (Séré et al. 2008; Séré et al. 2010) and which are capable to provide many ecosystem services (Morel et al. 2015). Such constructed Technosols (IUSS 2014) also exhibit the advantage of recycling various wastes and by-products from the contaminated site treatment (e.g., bioremediated and thermally treated earth materials), as well as local industrial activity (e.g., paper mill sludge, fly ash) and even urban wastes (e.g., sewage sludge, green waste, demolition rubble) (Rokia et al. 2014), and thus avoid the consumption of natural resources.

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Previous studies focused on several provided functions and demonstrated the capacity of constructed Technosols to produce biomass (Séré et al. 2008), to store some available water for plants (Yilmaz et al. 2018), to create porosity (Jangorzo et al. 2013; Deeb et al. 2016), to contribute to organic matter transformation (Grosbellet et al. 2011), and to filter water (Séré et al. 2008). Yet, a very limited number of studies concerning the response/role of soil organisms and their biodiversity in constructed Technosols have been performed and these were predominantly conducted at the laboratory scale (Pey et al. 2013; Jangorzo et al. 2014; Pey et al. 2014). Hafeez et al. (2012) were able to successfully monitor the in situ evolution of soil microbial communities and their variabilities in such ecosystems. The authors concluded that the abundance and diversity of the microbial communities were comparable with similar agricultural soils. It is now largely recognized that soil functions are performed or improved by soil biota (Lavelle et al. 1997; Briones 2014). For instance, earthworms are considered as engineers of soil ecosystems, because they are particularly able to transform and improve soil physical structure (Jones et al. 1994).

Questions remain on the following: (i) the nature and succession of the processes during the early phase of colonization of constructed Technosol systems, (ii) the ability of soil invertebrates to survive in such artificial environments, (iii) the contribution of biological activity to the pedogenesis of constructed Technosols. This study is based on a 4-year monitoring of two distinct in situ constructed Technosols (0.5 ha). As biodiversity is a multi-faceted concept, we investigated both its taxonomic and functional components.

2 Materials and methods

2.1 Experimental site

Experimentation was carried out at the French Scientific Interest Group—Industrial Wasteland site (Homécourt, Lorraine region, North-Eastern France) (www.gisfi.fr). The climate is continental with a mean rainfall of 760 mm year^{-1} and a mean temperature of 10 °C (Fig. 1). Mean temperature over the 3 months before invertebrate samplings were 4.5 °C, 1.8 °C, 1.8 °C, and 4.1 °C for 2008, 2009, 2010, and 2011 respectively. Two 0.5-ha demonstration plots were implemented in autumn 2007. Each 0.5-ha plot was divided into 12 sampling units of 20 × 20 m.

2.2 Constructed Technosols

Details of the pedological engineering process and initial properties of the Technosol have been extensively described by Séré et al. (2010). Three distinct technogenic parent materials were used: paper-mill sludge (PS), thermally treated industrial soil (TIS), and green-waste compost (GWC). Two different constructed Technosols declinations were implemented on the two 0.5 ha plots: (1) "Water buffer" with, from the bottom to the top, 15 cm of pure PS, 70 cm of TIS + PS mixture (1/1 volumetric ratio), and 10 cm of GWC and (2) "Containment" with, from the bottom to the top, 15 cm of limed and compacted PS, 70 cm of TIS + PS mixture (1/1 volumetric ratio), and 10 cm of GWC. The two constructed

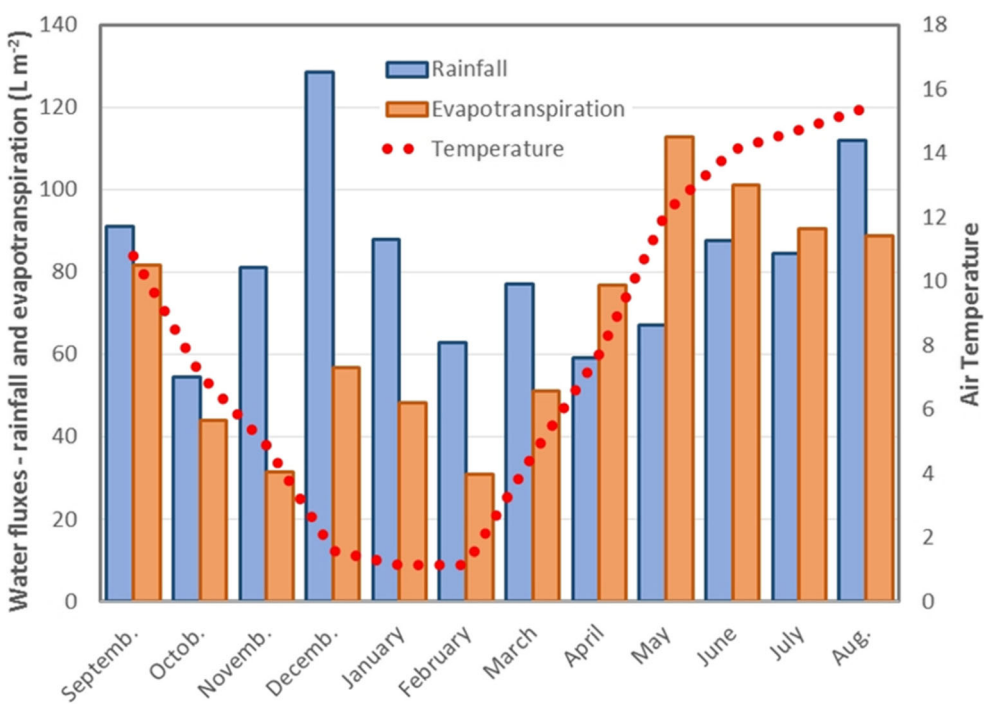

Fig. 1 Climatic data of average monthly rainfall, actual evapotranspiration, and air temperature in Homécourt (France) between 2008 and 2012

Technosols are both classified as Spolic Garbic Hydric Technosol (Calcaric) (IUSS Working Group WRB 2014).

Regarding soil contaminants, the total trace element concentrations were, on average, comparable to the natural geochemical background (Table 1). Some elements were below this threshold (Cd, Cr, Co, Ni) or in the same order of magnitude (Cu, Zn). Pb concentration was five times higher than the geochemical background, but remained within the range of concentrations that can be found in natural soils. The 16 PAH concentrations were much higher than in the geochemical background even after the soil treatment operation. However, such a level of organic pollutants is not expected to generate any significant toxicity or health risk.

In order to establish a meadow, a mixture of grass plants were sown in November 2007 (30% *Lolium perenne*, var. Tove; 40% *Festuca arundinacea*, var. Fuego; 30% *Dactylis glomerata*, var. Amba). The vegetation was mown and mulched twice a year without any exportation. The average dry biomass production over the 4 years studied (2008 to 2011) was 3 t ha^{-1}, which is comparable to neighboring natural extensive meadows.

2.3 Monitoring of soil properties

Surface soil (0 to 15 cm) was sampled within each of the 24 subplots in the first half of April of each year (2008 to 2011). The soil agronomic parameters (pH, C_{org}, N, $CaCO_3$, available P, and texture) were measured yearly in spring on all the subplots. All soil analyses were carried out by the "Laboratoire d'Analyze des Sols' (INRA, Arras, France) applying French standard (NF) of International Organization for Standardization (ISO) and quality assurance procedures assessed by the French Committee of Accreditation. Soil pH determination was performed according to NF ISO 10390 (2005), total organic C and N according to NF ISO 10694 (1995), $CaCO_3$ according to NF ISO 10693 (1995), available P (Olsen method) according to NF ISO 11263 (1994) and texture according to NF X31-107 (2003).

2.4 Invertebrates sampling and identification

Samplings were taken in the first half of April every year from 2008 (0.5 year) to 2011 (3.5 years). Each year on each sampling unit of 20 × 20 m ($N = 24$), two microhabitats were sampled by a combination of methods. Surface active (= epigeic) macro-invertebrates were sampled using pitfall traps. One trap (7-cm diameter) per subplot was put in the soil and partly filled with alcohol vinegar used as a killing and preservative medium. Traps were left for 1 week and the collected contents preserved in ethanol (70%) for further identification. At the same sampling point, we hand sorted soil-dwelling macro-invertebrates from a 25-cm × 25-cm × 20-cm monolith of soil. Animals were stored in ethanol (70%). In the laboratory, adult invertebrates were identified at least at the family level and most of them at species level, like e.g. earthworms, woodlice, scarab beetles, clown beetles, centipedes, lady beetles, ground beetles and spiders. The Fauna Europaea (De Jong et al. 2011) database was used as standard for invertebrate taxonomy.

2.5 Data analyses

To characterize the relationships between different measured soil parameters over time, we performed a principal component analysis (PCA). Analyses and graphical displays were produced with the ade4 library for R software (Dray and Dufour 2007).

We aimed at selecting a set of indices that assesses the dynamics of invertebrate communities in the constructed Technosols over time. While some of the available indices are difficult to interpret at first sight, it is more informative to assess several indices to describe the different facets of the dynamics of soil organisms' communities (see Electronic Supplementary Material).

Abundance is given as invertebrate density in the soil and density-activity at the soil surface. The density of soil-dwelling invertebrates, expressed as the number of individuals per m^2, was calculated on the basis of the abundance obtained by hand sorting. We computed the density of all collected soil-dwelling invertebrates. We also computed this density of the taxonomic groups representing the major part of the density, namely the earthworms (Lumbricidae), the ground beetles (Carabidae), the spiders (Araneae), the crane-fly larvae (Tipulidae), the woodlice (Isopoda), and the snails/slugs (Gastropoda). The density-activity of epigeic invertebrates was expressed as the number of individuals collected per trap.

Table 1 Mean and standard error ($N = 24$) of total trace elements and 16 PAH concentrations in the 30 first centimeters of the two constructed Technosols and natural pedo-geochemical background of the surrounding natural soils

	Cd	Cr	Co	Cu	Ni	Pb	Zn	16 PAH
	mg kg^{-1}							
constructed Technosol	1.8 (0.3)	57.8 (9.1)	10.6 (2.2)	51.0 (13.5)	25.2 (5.1)	130.4 (29.5)	381.7 (59.8)	40.1 (6.2)
natural pedo-geochemical background*	2.0	80.0	15.0	15.0	30.0	25.0	120.0	1.0

*Darmendrail et al. (2000)

We computed the density of all collected epigeic invertebrates. We also computed the density of the taxonomic groups representing the major groups, i.e., the spiders (Araneae), the ground beetles (Carabidae) and the woodlice (Isopoda). Temporal dynamics and Technosol type effects on density and on density-activity were tested with linear mixed effects model with "year" and "type" as fixed factors and "sampling point" as random factor, using *nlme* library for R software.

We used a unified approach that estimates the taxonomic diversity profile of an assemblage (Chao et al. 2014), based on the Hill number ^{q}D or the "effective number of species" (Gotelli and Chao 2013). When $q = 0$, the species relative abundances do not count, and ^{0}D equals species richness. ^{1}D is the exponential form of Shannon–Wiener index and can be interpreted as the number of "common species" in the assemblage. ^{2}D approximates the number of "dominant species" in the assemblage. Hill numbers are continuous and can be portrayed on a single graph as a function of q, leading to a "diversity profile" of effective taxonomic richness. The diversity profile curve is a decreasing function of q, thus the more uneven the distribution of relative abundances, the more steeply the curve declines. We used the "entropart" library for R software to compute the diversity profiles of soil and epigeic assemblage species per year and per Technosol type (Marcon and Hérault 2013).

Since species diversity and species composition may change independently, we investigated the year-over-year assemblage heterogeneity for each Technosol type. This was estimated from the dissimilarity in invertebrate assemblages between years, by permutational multivariate variance analysis (permanova). This approach partitions the variability in the dissimilarity matrix due to the selected factors using permutations (McArdle and Anderson 2001). We used this approach with 1000 permutations on pairwise Bray–Curtis dissimilarities. Pseudo-F ratios were computed to test the significance of plot age. To graphically represent the community changes, we log-transformed [log(x + 1)] species abundance data for a given sampling point and year and then performed a non-metric multi-dimensional scaling (NMDS), with Bray–Curtis dissimilarities as distances. Rare species (singletons and doubletons) were discarded before analysis. NMDS and permanova were carried out for soil and epigeic assemblages, using the vegan library for R software (Oksanen et al. 2011).

Colonization dynamics also have to be investigated through changes in the biological functions displayed within the assemblage. Dispersion and settlement ways differ between taxonomic groups, e.g., by walk, flight, and passive transport, rendering it difficult to depict the overall macrofauna response. Additionally, traits are not available for all taxonomic groups. Hence, we chose to focus on earthworms, spiders, and ground beetles, which we identified at species levels and for which traits are available at species level in databases. First, we described changes in body size. Colonization ability was deduced from ballooning dispersion for spiders, wing morphology for ground beetles and earthworm ability to crawl at soil surface. Settlement in the meadow was studied through selected life history traits, granivory for ground beetles, and ability to parthenogenetic reproduction for earthworms.

Additionally, we hypothesized that the distribution of individuals in trophic groups changes across time, with a particular increase in proportions of primary consumers (phytophages) and litter consumers (detritivores) in the assemblages. Traits were extracted from the BETSI database (http://betsi.cesab.org). For each trait, we calculated the mean value of community (CWM), which corresponds to the sum of the taxa affinities for a trait, weighted by the taxa relative abundance in the community (Garnier et al. 2004). The patterns of CWM diet were represented in triangular plots (Hedde et al. 2013). Temporal dynamics of macroinvertebrate dispersal traits were tested with linear mixed effects models with "year" and "type" as fixed factors and "sampling point" as random factor, using *nlme* library for R software (Pinheiro et al. 2016).

3 Results

3.1 Changes in physico-chemical properties of the Technosols over time

The organic carbon content of the assessed Technosols slightly decreased over 4 years for both treatments (from 85.2 to 80.5 g kg^{-1} for the containment treatment and from 89.7 to 87 g kg^{-1} for the water buffer one) (Table 2). The nitrogen and total phosphorus contents also decreased significantly over the studied period for both treatments (Table 2). No significant evolution of the calcareous content (Table 2) was observed as the variability of the measured data was high due to the parent material heterogeneity. All these data have to be considered by taking into account the settlement of the constructed Technosols that should normally lead to an increase of the concentrations due to the increase of the bulk densities (Séré et al. 2010). As previously described by Jangorzo et al. (2013), the soil compaction led to a decrease of pores surface but surprisingly to an increase of both number of pores and pores connectivity (Table 2). There was a decrease of the finer granulometric fractions (< 2 μm) and an increase of the coarser one (50–2000 μm) (Table 2). This phenomenon might be the result of a vertical transfer of clays within the soil profiles. There was a slight increase in soil pH (from 8.1 to 8.5).

It has to be noticed that waterlogging events were recorded in the "containment" Technosol—at least during 4 months in 2008 and 1 month in 2009, while only one waterlogging event lasting 2 months was observed in the "water buffer" Technosol in 2008.

The changes in measured soil parameters evolved with time and were additionally strongly linked to the properties of the

Table 2 Mean ($N = 12$) physico-chemical parameters of the upper horizons of two constructed Technosol

		Containment				Water buffer			
		0.5	1.5	2.5	3.5	0.5	1.5	2.5	3.5
Granulometric fractions (g kg^{-1})	< 2 μm	276.6	187.0	141.4	171.4	236.8	168.5	146.3	161.7
	2–50 μm	147.5	142.8	109.8	130.9	160.9	169.7	141.7	139.0
	50–2000 μm	140.8	208,0	291.1	235.8	214.8	247.7	301.5	306.3
Total nitrogen (g kg^{-1})		3.9	3.0	2.7	2.5	3.3	2.9	3.0	2.4
Organic carbon (g kg^{-1})		85.8	77.9	78.1	80.5	89.7	82.9	85.2	87,0
pH		8.1	8.3	8.3	8.5	8.3	8.3	8.3	8.5
Calcite (g kg^{-1})		426.9	453.2	449,0	451.1	377.9	405.7	402.4	384.2
Total phosphorus (g kg^{-1})		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Cation exchange capacity ($cmol^{+}$ kg^{-1})		14.3	NA	12.7	13.3	13.4	NA	13.3	13.8
Poral architecture (Jangorzo et al., 2013	Number of process	2828	NA	4177	NA	3244	NA	4529	NA
	Pores surface	21.7	NA	15.1	NA	23.5	NA	17.8	NA
	Pores connectivity	0.28	NA	0.31	NA	0.34	NA	0.36	NA

Technosols treatments (first plan PCA with CP1 = 39% and CP2 = 27%, see Fig. 1). The barycenter of younger soils (1-year old) displayed negative coordinates on the first PCA axis (PC1). As the soils evolved, the barycenter coordinates increased on PC1. This was explained by changes in the nutrients. Sand content, pH and C:N ratio negatively correlated with PC1 and clay, P_{Olsen} and N_{tot} content increased with PC1. $CaCO_3$ content had a strongly positive correlation with PC2 and C_{org}, loam and sand content had negative correlations with PC2.

3.2 Dynamics of density and density-activity of invertebrates

A total of 3880 individuals was collected over the 4 years of the study, and 89 species were identified. The density or the density-activity of all taxonomic groups were highly significantly influenced by Technosol aging. Few differences were noticed between the two constructed Technosols, still some interactions between the two factors (soil type and age) revealed differences in colonization dynamics between the two treatments (Table 3). At the end of the assessment period of 4 years, the total density of soil-dwelling macro-invertebrates reached 1044 and 619 individuals m^{-2} in "containment" and "water buffer" Technosols, respectively, which were not colonized at study start. After 4 years, earthworms dominated soil-dwelling assemblages, representing 33% of soil macrofauna density. Earthworm colonization was faster in the "containment" Technosol but no significant differences in density between treatments were recorded after 4 years. Ground beetles and crane fly larvae were only influenced by soil aging while spiders, molluscs, and woodlice pattern of colonization varied depending on the nature of the constructed Technosol (Table 3).

The total density-activity of epigeic macro-invertebrates grew significantly with soil aging, reaching about 36 individuals per trap after 4 years. This increase was mostly driven by the spiders that represented more than half of animals collected. Differences between the two treatments of Technosols were observed for woodlice, with faster colonization and higher individual density in "containment" Technosol.

3.3 Dynamics of species diversity and composition

The temporal dynamics of the species diversity is illustrated through the species diversity profiles in Fig. 2. A similar global trend arose for total assemblages, either soil-dwelling (Fig. 3a) or epigeic (Fig. 3b) as for many taxonomic groups. From 2 to 3 and to 4 years, species diversity profiles characterized higher rare species number with an unchanged number of dominant species since the steepness of the curve increased and the effective number of species increased for low values of q while remaining stable or a little lower for high values of q. Additionally, as time after establishment of the Technosols passed, species diversity curves became steeper and steeper for q values less than 1, meaning that species diversity changes related more to rare species than to common or dominant species. Additionally, the "containment" Technosol tended to have higher species diversity than the "water buffer" one. Too few earthworm species were present to draw a trend. Interestingly, spiders were more diverse in the "water buffer" Technosol (Fig. 3c), while ground beetles had higher levels of species diversity in the "containment" Technosol (Fig. 3d, e).

A high temporal turnover of the recorded species during the course of the monitoring was detectable—as seen in the results of the Permanova ($p < 0.001$ for both soil-dwelling and epigeic invertebrates). Moreover, the composition of both soil-dwelling ($p < 0.5$) and epigeic ($p < 0.05$) invertebrates was affected by the type of Technosol investigated. Changes

Table 3 Mean ($N = 12$) and standard error of taxonomic-based parameters of macro-invertebrates assemblages in the soil and at the soil surface of two constructed Technosols

Parameter	Technosol type	Containment				Water buffer				Fadors' effects		
	Soil age (year)	0.5	1.5	2.5	3.5	0.5	1.5	2.5	3.5	Age	Type	AxT
Density (individuals n^2)	all	0.0 (0.0) d	267.6 (61.9) b	298.2 (62.5) b	1044.4 (224.3) a	0.0 (0.0) d	109.5 (23.4) cd	374.2 (55.9) b	619.1 (72.1) a	< 0.001	ns	< 0.005
	Tipulidae (L)	0.0 (0.0) c	0.0 (0.0) cb	4.4 (2.1) ab	36.4 (21.5) a	0.0 (0.0) c	7.4 (3.7) cb	19.7 (8.4) ab	66.5 (24.6) a	< 0.001	ns	ns
	Lumbricidae	0.0 (0.0)c	11.6 (8.3) b	27.6 (13.6) b	352.0 (58.4) a	0.0 (0.0) c	0.0 (0.0) c	19.7 (15.2) b	182.2 (38.0) a	< 0.001	< 0.05	< 0.01
	Aran ea. e	0.0 (0.0) d	21.8 (6.9) b	26.2 (8.3) ab	50.9 (13.4) a	0.0 (0.0) d	7.4 (2.4) c	43.1 (11.5) a	27.1 (6.4) ab	< 0.001	ns	< 0.01
	Carabidae	0.0 (0.0) c	11.6 (8.3) b	27.6 (6.6) a	50.9 (14.7) a	0.0 (0.0) c	11.1 (3.9) b	43.1 (11.2) a	34.5 (7.7) a	< 0.001	ns	ns
	Gastropoda	0.0 (0.0) c	0.0 (0.0) c	0.2 (0.2) b	0.3 (0.2) b	0.0 (0.0) c	0.2 (0.2) b	1.3 (0.5) a	0.2 (0.1) b	< 0.001	< 0.05	< 0.005
	Isopoda	0.0 (0.0) d	8.7 (5.6) bc	29.1 (16.0) abc	72.7 (21.7) a	0.0 (0.0) d	1.2 (1.3) cd	32.0 (13.6) ab	16.0 (5.3) b	< 0.001	< 0.01	< 0.01
Density-activity (individuals pertrap)	All	0.0 (0.0) c	20.1 (2.9) b	23.9 (3.9) ab	35.5 (8.1) a	0.0 (0.0) c	17.2 (3.6) b	23.5 (2.3) ab	36.1 (6.1) a	< 0.001	ns	ns
	Araneae	0.0 (0.0) c	10.3 (2.2) b	15.3 (4.2) ab	23.0 (5.6) a	0.0 (0.0) c	10.3 (2.4) b	9.7 (1.7) ab	21.8 (4.6) a	< 0.001	ns	ns
	Carabidae	0.0 (0.0) d	5.9 (1.2) b	2.5 (0.7) cd	7.8 (2.7) b	0.0(0.0) d	3.5 (1.1) bc	5.2 (1.1) ab	9.2 (1.7) a	< 0.001	ns	< 0.01
	Isopoda	0.0 (0.0) c	0.0 (0.0) c	0.4 (0.2) bc	2.2 (0.5) a	0.0 (0.0) c	0.0(0.0) c	0.1 (0.1) c	0.8 (0.4) ab	< 0.001	< 0.05	< 0.005

Different letters indicate significant differences at the rejection threshold $\alpha = 0.05$

in species composition over the years and differences between the two investigated Technosols can be seen in Fig. 4. Changes in community composition were thus influenced by years but not related to soil aging.

3.4 Dynamics of functional traits composition

The mean body length of the spider community varied with soil aging but not within Technosol treatment, with values increasing from 4 to 5 mm after 2 years to 7 mm 2 years later (Table 4). The proportion of ballooning individuals highly decreased as soil aged, from 80 to 7% in the "containment" treatment and from 50 to 18% in the "water buffer" treatment. However, the significant interactive effect between year and Technosol type indicates that the changes are not similar in both treatments (Table 4).

The mean chosen trait values of ground beetle communities were only influenced by years but not related to soil aging. The mean body length was about 8–9 mm after 2 and 4 years, but was much lower, about 6 mm, after 3 years (Table 4). Macropterous individuals dominated assemblages, with higher proportions after 4 years (80%) than before (47–59%). Similar results were obtained for the proportion of granivorous individuals, i.e., 27–38% during the first 2 years and 52–55% after 4 years.

Community-weighted mean traits of earthworms were not influenced by the factors (time and Technosol type) or by their interaction (Table 4). The mean proportion of surface-crawling and parthenogenetic individuals were 81.9% (± 1.7%) and 71.5% (± 0.5%), respectively, and the mean body length was 106 (± 4.5) mm.

The dynamics of diet repartition in three trophic regimes (phytophage, zoophage, and detritivore) within the community assessed showed more consistent differences (Fig. 5). In soil, the proportion of detritivores increased up to 60 and 48%, for "containment" and "water buffer" Technosol, respectively. At the soil surface, zoophages dominated (76–97%). While rather weak, a settlement of phytophages and detritivores in both Technosols can be reported after 4 years.

4 Discussion

During the early phase of colonization of an ecological system, classical succession theory supposes the migration, arrival, settlement, and growth of new populations (Gleason 1917). Thereafter, the community assembly mechanism is proposed to describe a shift from random (e.g., propagules dispersion) to interspecific (e.g., competition) processes to reach a steady state or a dynamic equilibrium. Our results supported the hypothesis that macro-invertebrates can colonize the Technosols very rapidly after construction.

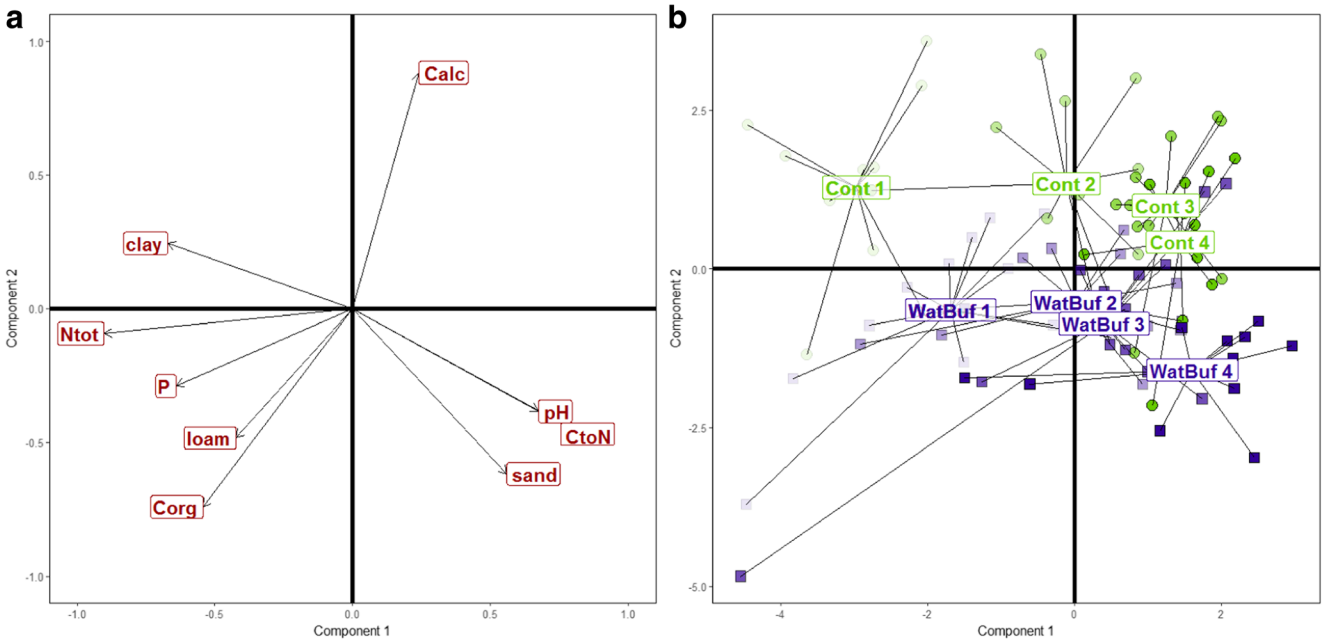

Fig. 2 Results of the PCA on soil agronomic characteristics **a** projection of the variables on the correlation circle, **b** first factorial plan of PCA, samples are grouped by Technosol type ("Cont" for containment and "WatBuf" for water buffer) and by year

4.1 Early pedogenesis

The pedological characterization showed that these constructed Technosols have specific physico-chemical characteristics. Soils are carbonated, rich in organic matter, with moderate chemical fertility, and a good physical fertility compared to agronomic standards. The organic carbon content is much higher than in analogous natural meadows, whereas the total nitrogen and the available phosphorous concentrations are moderate to low compared to non-anthropized soils (Rokia et al. 2014). The calcareous content is notably high in the "containment" Technosol and could cause some ferric chlorosis issues. The wastes and by-products that were used as parent materials for the construction of the Technosols were chosen for their acceptable levels of contamination. As a consequence, the concentrations in pollutants were comparable to the natural pedo-geochemical background. The first factorial plan of PCA on agronomic soil parameters clearly displayed a gradient of development. pH and C:N ratio increased during development, while high values of nutrients (N and P) were correlated with initial stage. pH increase during soil aging of a Technosol was already reported (Séré et al. 2010). C/N increase would correspond to the input of both shoot and root litter into the soil. Given the lack of correlation of $CaCO_3$ content with pH, pH evolution appears to be related to $CaCO_3$ dissolution in the GWC layer and a precipitation in the PS layer. N and P content were inversely correlated with PC1, meaning that a part of N and P pool—probably the most labile—was incorporated into the biomass and leached to deeper horizons (Séré et al. 2010). The second axis of the PCA was clearly linked to the use of limed PS at the bottom of the containment Technosol.

4.2 Dynamics of density and density-activity of invertebrates

We show that constructed Technosols as the ones investigated can host numerous macro-invertebrates rapidly after construction. This is in accordance with knowledge about macrofauna recolonization abilities (de Araújo et al. 2015; Puga et al. 2016). The results fall within the range of previous works on (re)colonization by soil fauna. Whereas the macrofauna was absent at the beginning of the monitoring, after 4 years, we recorded 1044 and 619 individuals m^{-2} (in containment and water buffer Technosols, respectively) and about 36 individuals per trap and week. This is much higher than the values obtained by Hedde et al. (2013), with the same sampling methodologies, in soils of metal contaminated lands in Paris Basin rehabilitated by energy crop plantation. The high density of dipteran and coleopteran larvae in grassland soil is a common pattern (Seeber et al. 2005). The density of earthworms in the present Technosols is low to moderate and the dynamics of colonization rather slow during the first 2 years (< 20 individuals m^{-2}, respectively). However, this value is within the range observed during early earthworm colonization, for instance in reclaimed post-mining areas (Frouz et al. 2001), after field abandonment (Pižl 1992), in crop-pasture rotation (Decaëns et al. 2011), or to the dynamics of earthworm population development after inoculation in a landfill site (Butt et al. 2004). The sudden increase in earthworm density during the fourth year is rather comparable with the pattern highlighted by Decaëns et al. (2011), who reported a 13-fold boost in density in less than 2 years of pasture after annual cropping in Normandy (France). The low density of endogeic

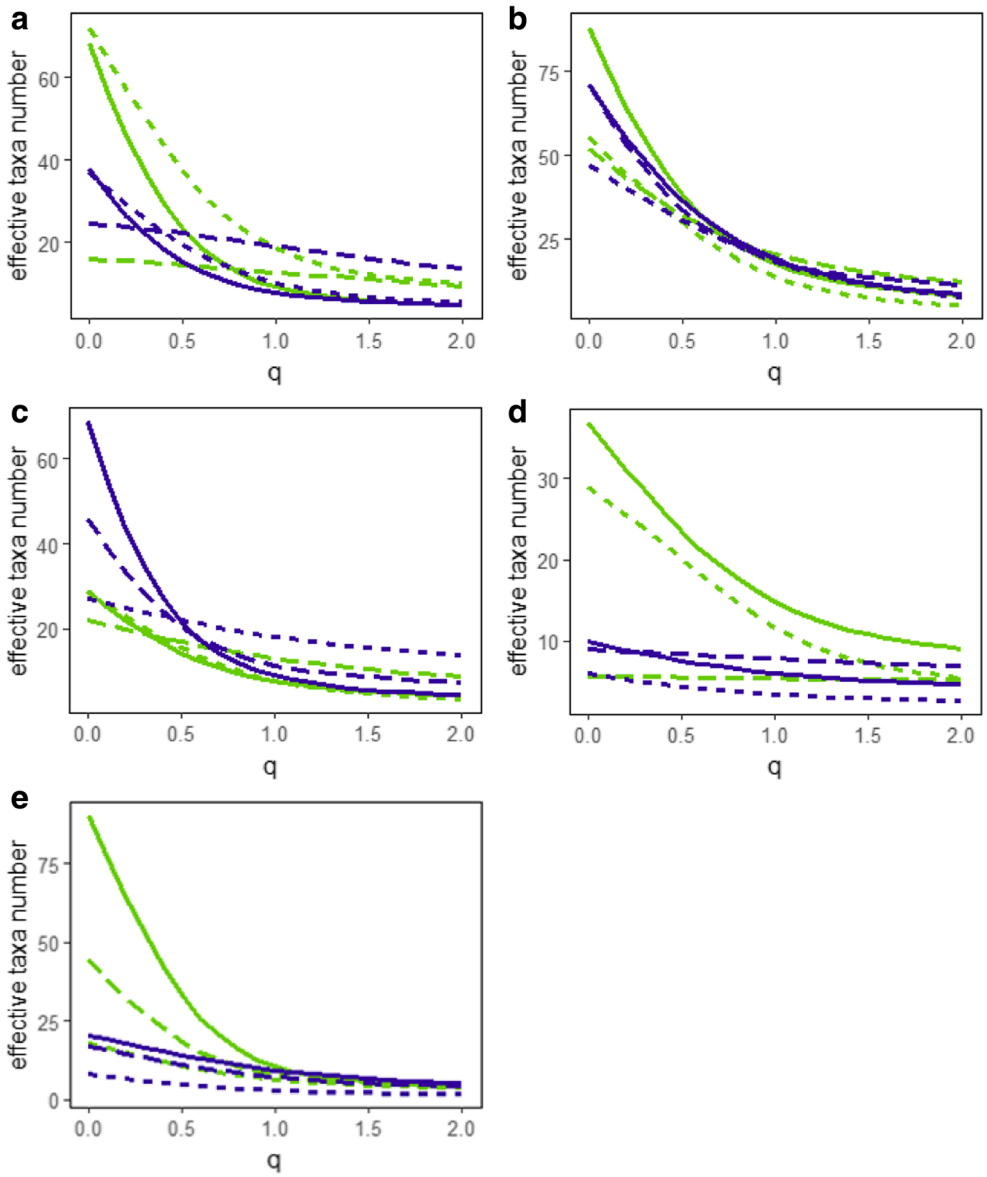

Fig. 3 Species diversity profiles in the soil of the two Technosol fields over 4 years. **a** All soil-dwelling invertebrates species, **b** All epigeic invertebrates species, **c** epigeic spider species, **d** soil-dwelling carabid species, **e** epigeic carabid species. Green: containment treatments, blue: water buffer treatment. Year 2: dotted line, year 3: dashed line, and year 4: solid line

earthworms in our study is in accordance with Roubíčková and Frouz (2014), who recently demonstrated that colonization of heaps by the endogeic earthworm *A. caliginosa* is enhanced by vegetal succession and is rather low during the early stages. It is interesting to point out that temperature may have played a role in the higher increase in invertebrate density or density-activity in the fourth year since temperature during the 3-month preceding samplings was milder in the fourth year (4.8 °C in average) compared to that of the previous years (1.8 °C in average). In ectotherms, higher temperature may have enhanced the life history traits (e.g., growth and fecundity) of winter active invertebrates like earthworm and may have hastened imaginal molting for spring insects. Finally, an interesting point was that it suggest that the carrying capacity of these Technosols has not yet been exceeded after 4 years.

4.3 Dynamics of species diversity and composition

Changes in the species diversity profile over years were similar between taxonomic groups, the soil and the surface of the Technosol hosting more and more diverse assemblages. Furthermore, changes in the species diversity profile showed that individuals were less evenly distributed within species, including more rare species as the Technosol develops. Rare species increase is an important feature for ecosystem functioning, since they have been documented to participate in ecosystem functioning (Hooper et al. 2005). Diversity profiles were quite different between the two constructed Technosols. Except for spiders, "containment" Technosol hosted higher species diversity with a greater temporal differentiation than in the "water buffer" Technosol.

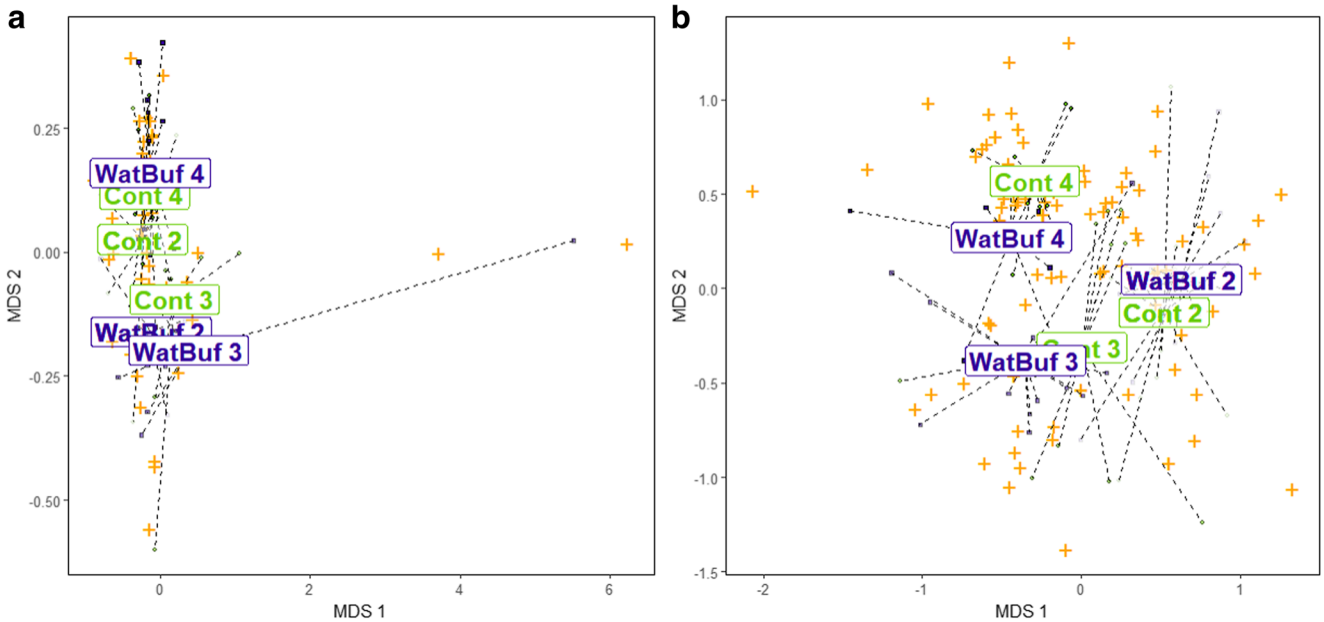

Fig. 4 NMDS biplot ordinations for soil (**a**) and epigeic (**b**) macroinvertebrate assemblages; with Bray-Curtis dissimilarity as the distance between species assemblages. Points (= sampling points) are grouped by Technosol type ("Cont" for containment and "WatBuf" for water buffer) and by year

Detected differences in species composition on Technosol treatment and Technosol age for epigeic communities and depending on Technosol age for soil-dwelling communities showed that soil and epigeic assemblages did not have the same turnover dynamics. At the soil's surface, there was a gradient from 2 to 3 to 4 years after Technosol construction. Conversely, the temporal dynamics of soil invertebrate assemblages lead to similar assemblages after 4 years but with different pathways between the Technosols. This can be interpreted as a continuous process of succession for epigeic invertebrates. Conversely, the turnover of soil invertebrates may incorporate more stochasticity, with thresholds depending on for instance nutrient limitation, the lack of a key species (e.g., anecic worms) or on differing environmental impacts in the two Technosols (e.g., water logging, soil moisture). Soil engineering questions are of great interest to explain the interplay between soil and epigeic invertebrate colonization/succession according to the evolution of their habitat.

4.4 Dynamics of functional traits composition

As hypothesized, functional traits of spiders and ground beetles varied with soil aging. The mean body size of the spider community increased. This was reflected by a lower proportion of aerial dispersers, as there is a threshold mass that permits ballooning. Along the 3-year period, an important shift in spider strategy was thus observed. The last year, a massive proportion of ground beetles (80%) has macropterous wings and half of them were granivorous. This could reflect the arrival of a prairial community, with numerous seed-eaters. Three years is thus a too short period to detect the settlement of such a community. Mean earthworm traits showed no

Table 4 Mean ($N = 12$) and standard error of community-weighted functional traits of spiders and ground beetles in the soil and at the soil surface of two constructed Technosols

	Technosol type	Containment			Water buffer			Factors' effects		
	Soil age (year)	1.5	2.5	3.5	1.5	2.5	3.5	Age	Type	AxT
Spiders	Max body length (mm)	4.2 (0.3) c	5.5 (0.4) b	7.3 (0.2) a	5.0 (0.2) c	6.0 (0.3) b	7.3 (0.2) a	< 0.001	ns	ns
	Ballooners (%)	80.2 (2.4) a	51.9 (5.2) b	6.9 (0.8) c	49.2 (2.6) b	18.2 (3.1) c	18.2 (3.1) c	< 0.001	ns	
Ground beetles	Max body length (mm)	8.0 (0.3) a	6.4 (0.3) b	8.8 (0.2) a	9.2 (0.5) a	9.9 (0.2) a	9.9 (0.2) a	< 0.001	ns	ns
	Macropterous (%)	49.5 (3.2) b	51.8 (2.5) b	80.9 (2.1) a	59.0 (3.0) b	79.2 (2.5) a	79.2 (2.5) a	< 0.001	ns	ns
	Granivorous (%)	38.2 (1.4) b	36.6 (0.2) b	55.0 (2.5) a	27.5 (1.9) b	52.4 (2.9) a	52.4 (2.9) a	< 0.001	ns	ns

Different letters indicate significant differences at the rejection threshold $\alpha = 0.05$

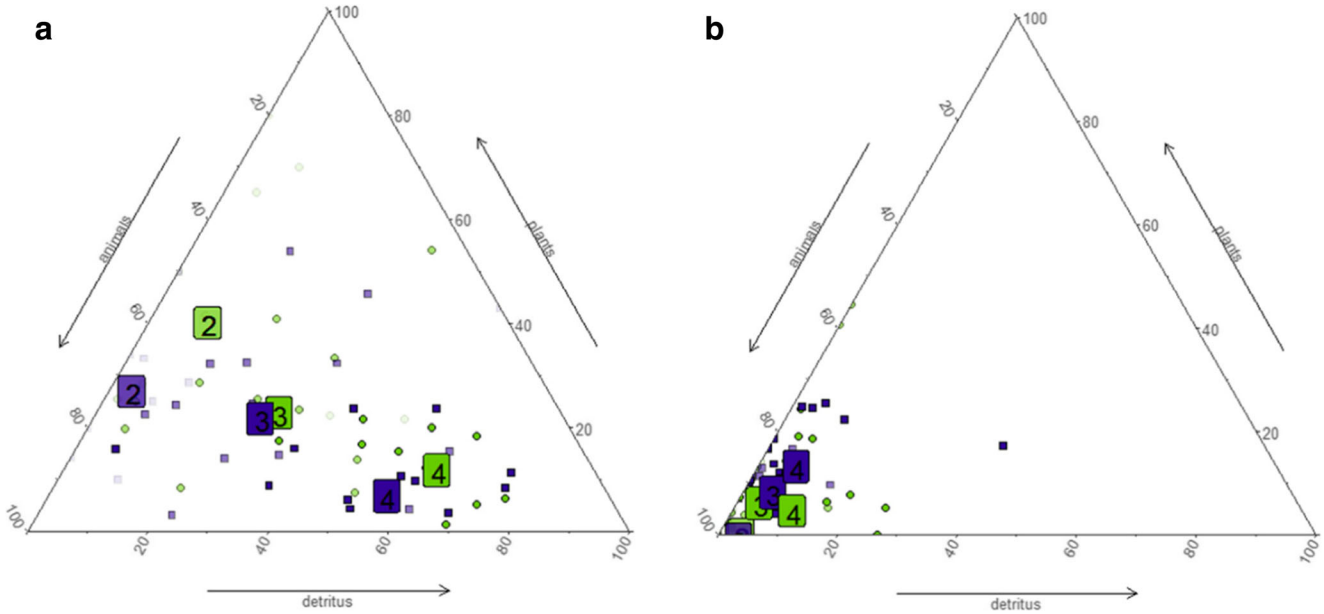

Fig. 5 Dynamics of community-weighted mean (CWM) food preference in soil (left panel) and epigeic (right panel) invertebrate assemblages in ternary representations, small symbols are sampling point values, large symbols are the barycenters of CWM by Technosol type (green for containment and blue for water buffer) and by year

variation over the years, independently from the treatment. So, we thus argue that earthworms were still in their initial phase of colonization.

In soil assemblages, the distribution of individuals between feeding groups changed significantly and in a similar way for both Technosols. We observed a temporal increase in the proportion of detritivores that reached 53% after 4 years. Since there was little species turnover, such an increase relate to the settlement/development of a few populations of detritivore species. This implies that detritus degradation was achieved by a large number of individuals belonging to just a few species. Then, questions arise about the redundancy on this crucial function. Does this low number of species interact synergistically on litter degradation? What is the minimum number of interacting species required to maintain sustainable levels for this function? These questions have already been addressed in the laboratory (Heemsbergen et al. 2004; Zimmer et al. 2005; Hedde et al. 2010), but deserve more attention in the field, incorporating temporal dynamic aspects.

5 Conclusions

The constructed Technosol, on which a meadow was sown and well established after 4 years, can host numerous soil macro-invertebrates. In addition, an unambiguous increase in diversity was monitored throughout the duration of the study. The results on species diversity and composition enable us to state that macro-invertebrate communities are still being in a colonization phase. There are, at least, two future directions for studies of this type. Knowledge (i) of long-term colonization dynamics and (ii) of biodiversity-ecosystem functioning relationships are required to comprehensively assess the evolution of a constructed Technosol. Additionally, the potential of a constructed Technosol as sustainable way to reclaim derelict lands will entail the semi-quantitative evaluation of the ecosystem services delivered by soil invertebrates.

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