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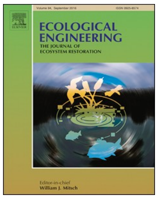

Tree growth and macrofauna colonization in Technosols constructed from recycled urban wastes

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ABSTRACT

Urban greening is a growing societal demand but consumes large amounts of soil. This massive transfer of soil, typically imported from peri-urban and rural areas, raises questions about the environmental sustainability of such projects. It has been suggested that artificial soils made with urban wastes, also called constructed Technosols, might be a sustainable alternative. In this article, we examined during three years, different mixtures of excavated deep horizons of soil, crushed concrete and green waste compost, in order to (i) identify the most suitable mixture for growing trees; (ii) identify tolerant tree species among six different species; and (iii) assess macrofaunal colonization, a major driver of soil fertility, from the surrounding macrofaunal pool.

The mixture of excavated deep horizons and green waste compost led to the highest tree mortality. The best tree survival and growth, and quickest soil macrofaunal colonization were obtained with a mixture of 20% of excavated deep horizons, 10% of green waste compost and 70% of crushed concrete (*v*/v). The survival rate of species *Acer campestre* and *Prunus avium* was 100% but only 58% for *Carpinus betulus*. Our results show the construction of Technosols with urban wastes is a promising alternative for planting trees and hosting soil biodiversity within cities.

1. Introduction

Municipalities around the world are engaging in urban greening (see Glossary), and more specifically in urban forestry when it involves the presence of trees (Konijnendijk et al., 2006; Tan and Jim, 2017), on a grand-scale. North American cities have launched campaigns such as "One million trees" in the United States and 300,000 trees in Montreal (Morani et al., 2011; Direction des grands parcs et de verdissement and Soverdi, 2012; Hubacek and Kronenberg, 2013). These urban greening projects require vast amounts of soil substrate as a growth medium for plants (Damas and Coulon, 2016). The soil substrates used for urban greening projects are generally natural soils taken from adjacent rural areas (Thompson and Sorvig, 2008; Damas and Coulon, 2016; European Environment Agency and Swiss Federal Office for the Environment, 2016). This solution is poorly sustainable because natural soils are not renewable. The high demand and short supply mean that soils are being taken from ever-increasing distances from urban areas. As a consequence, the ecological and economic costs of importing soils from rural areas are continuously increasing (DEFRA, 2009; Damas and Coulon, 2016). Thus, alternatives to this massive transportation of soil is needed.

Construction and demolition wastes (see Glossary) are widely available because global urbanization results in an alarming production of such wastes. They account for approximately 30% to 40% of all waste in OECD countries (Wilson et al., 2015). Although recycling these wastes is a top priority, only a limited number of applications are based on these materials. The most common recycling practice for construction and demolition wastes is the transformation into recycled aggregates (Wilson et al., 2015). This "downcycling" avenue (Di Maria et al., 2018) does not have sufficient capacity to absorb the production of construction and demolition wastes in several countries, where markets are saturated. Ideally, the development of solutions that limit the transportation and processing of construction and demolition wastes, and which allow an upcycling of this material are desirable.

The recent and active field of research on constructed Technosols (see Glossary) aims at developing such solutions by transforming construction and demolition wastes into more valuable materials for reclamation and urban greening (Séré et al., 2008; Rokia et al., 2014;

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Grard et al., 2018). Designing artificial soils for urban greening is challenging because of the difficulty to meet both the needs of plants and the technical constraints associated with urban areas. For example, soils under pavements are intentionally compacted to high bulk densities to enhance their load bearing capacity, however excessively high compaction can impede root development and tree growth (Day et al., 1995). Artificial soils that contain excavated subsoil have been successfully used in various urban forestry projects (Cannavo et al., 2018; Yilmaz et al., 2018). This material, also called excavated deep horizons of soil (see Glossary) is produced in very large amounts and is particularly poorly recycled at present (Magnusson et al., 2015). For instance, excavated deep horizons can account for almost 45% in UK to 80% in France of total construction and demolition wastes (BIO Intelligence Service, 2011). It contains very low amounts of organic matter and its composition depends on the geological parent material (DEFRA, 2009). The effects of the addition of organic or/and structural materials on the survival and growth of different species of trees, and on the soil macrofaunal communities have not received much attention in the literature. As a consequence, there is no consensus on the effects of the different components nor on the ideal proportions for specific applications.

Here, we present a three-year field-scale experiment that assessed the potential of four constructed Technosols to sustain tree growth and soil macrofauna colonization, a reliable indicator of soil quality and fertility (Ruiz et al., 2011; Joimel et al., 2016). The Technosols were composed of three materials in varying proportions: (i) excavated deep horizons of soil, (ii) crushed concrete from demolition sites (see Glossary) and (iii) green waste compost (see Glossary). The aim of the study was to determine if different tree species were able to survive in our constructed Technosols and if so, which of the different mixtures of materials was the most suitable for tree growth and macrofaunal colonization. We expected higher rates of tree survival and growth in the treatment with organic material additions (Mathews et al., 2002; Layman et al., 2016), and lower growth and survival in the treatment with coarse material (Day et al., 1995). The few studies that have been carried out on macrofaunal colonization and succession in Technosols have shown that constructed Technosols can form habitats for macrofauna (Vergnes et al., 2017; Hedde et al., 2019). Just as litter deposition was shown to affect the quality and quantity of the resources available to macrofauna, thus affecting both the abundance and richness of macrofaunal communities (Decaëns et al., 1998), it was expected that the addition of compost would similarly affect resource availability for detritivores (Mathews et al., 2002). Accordingly, we expected faster colonization, higher density and diversity of organisms in mixtures to which compost was added.

2. Materials and methods

2.1. Composition of constructed Technosols

In this study, the three materials used to construct Technosols: (i) Excavated Deep Horizons of soil (EDH), (ii) Crushed Concrete (40-80 mm size fraction) (CC) and (iii) Green Waste Compost (GWC) (Fig. 2). The Excavated Deep Horizons and the Green Waste Compost were the same materials used in previous studies (Deeb et al., 2016b; Deeb et al., 2016a; Deeb et al., 2017). In the Île-de-France region, Excavated Deep Horizons is mainly composed of carbonated rock from alluvial sediments deposited during Eocene and characteristic of the Parisian Basin. In our experiment, the Excavated Deep Horizons contained 431 $g.kg^{-1}$ of carbonates (Deeb et al., 2016b, Deeb et al., 2016a, Deeb et al., 2017). Crushed Concrete replace the stones generally put in tree plantation holes to ensure a mineral and solid skeleton. This technique is developed by landscape planners aims at preventing soil compaction and subsidence due to car traffic and parking in cities, which is critical for the survival and the development of urban trees (Jim, 1993). The Crushed Concrete and the Excavated Deep Horizons were obtained from different places in Ile-de-France. The material was collected from different points in the discharge banks in order to form a sample representative of wastes present in the region. Green waste compost was used as the main source of organic matter in the artificial soils. The composting and the quality of materials respected the French norm NFU 44–051, which defines limit contents of nitrogen, phosphorous (P_2O_5) and potassium (K_2O; total $<$ 7% dry matter; see section 2.6.), trace metals (see section 2.6.), organic compounds, microorganisms, and a minimum of organic matter content ($\geq$ 20% of dry matter) for commercialisation of organic amendments. The Green Waste Compost was provided by Biodepe, a subsidiary of the private company ECT (Environnement Conseils & Travaux, Ahuy, France), which is in charge of organic waste repurposing.

Table 1
Tree mortality in each mixture of materials.

Technosols	Species with dead individuals	Proportion of death per species	Time (year) between planting and mortality event
EDH	*Carpinus betulus*	33%	1
EDH-CC	*Carpinus betulus*	66%	1
EDH-GWC	*Acer platanoides*	33%	1
	Acer pseudoplatanus	100%	1
	Carpinus betulus	66%	1
	Tilia cordata	66%	1&3
EDH-CC-GWC	*Acer platanoides*	33%	1
	Tilia cordata	33%	1

n = 3 trees per species and type of Technosols. *Acer campestre* and *Prunus avium*, with no mortality, were not included in the Table. Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost)

2.2. Experimental site and design

The experimental site (Fig. 1a) is located in the North of Île-de-France (Villeneuve-sous-Dammartin, 49°02′94.99"N; 2°63′55.14″E) and belongs to the private company ECT specialized in inert construction and demolition wastes storage. Millions of tons of Excavated Deep Horizons are available on this site, which is used as a discharge for construction and demolition wastes from the Ile-de-France region. The site is surrounded by woods and fields in the vicinity of the international airport, Roissy Charles de Gaulle (CDG, Roissy-en-France). The experimental plots were set up in an old excavated subsoil storage site that had been restored 15 years ago by covering excavated subsoil with topsoil and by planting trees (*Robinia pseudoacacia*; *Pyrus communis* and *Malus domestica*) and turf grass (Fig. 1b). In May 2013, the experiment was initiated by removing the soil to a depth of 1.20 m in 12 plots (12x7m each) and by filling with different constructed Technosols (total volume: 1210m^3; Fig. 1c and d). We prepared four constructed Technosols: (1) EDH (100% of Excavated Deep Horizons); (2) EDH – CC (30% of Excavated Deep Horizons and 70% of Crushed Concrete); (3) EDH – GWC (90% of Excavated Deep Horizons and 10% of Green Waste Compost); (4) EDH – CC – GWC (20% of Excavated Deep Horizons, 70% of Crushed Concrete and 10% of Green Waste Compost). In total, 12 plots (3 randomised replicates by mixture) were set up in May 2013 (Fig. 1d). The aim of the study was to determine the effects of adding Crushed Concrete and/or Green Waste Compost to Excavated Deep Horizons on both trees and macrofaunal communities and therefore the Technosol with 100% of Excavated Deep Horizons (EDH treatment) was the control treatment to which the other treatments were compared.

2.3. Initial physico-chemical properties of Technosols

In order to characterize the mixtures of materials presented in 2.1 at

Fig. 1. (a) Location of the Charles de Gaulle airport (CDG) and the experimental site (the white circle) in the Paris region; (b) The actual storage site of inert construction wastes and ancient site with topsoil converted to experimental plots (the rectangle); (c) Dimensions of plots and locations of trees (the large circles; Apl: *Acer platanoides*; Tc: *Tilia cordata*; Aps: *Acer pseudoplatanus*; Pa: *Prunus avium*; Cb: *Carpinus betulus*; Ac: *Acer campestre*), samples of macrofauna (the squares), physical and chemical samples of constructed Technosols (the little circles); (d) Positioning of plots with the different constructed Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost), and the three reference samples of surrounding soil for assessing macrofauna local community (ST). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

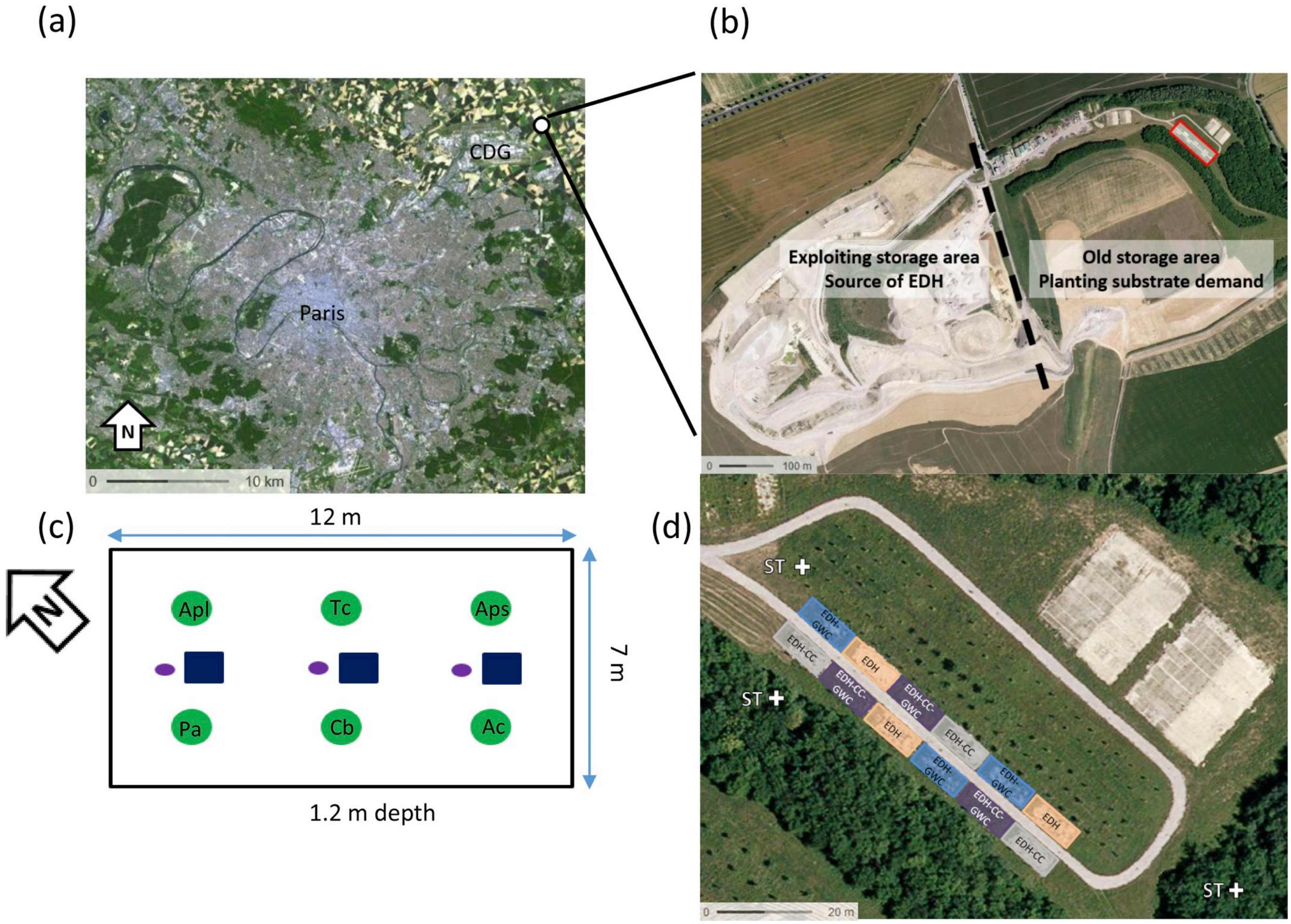

Fig. 2. (a) Excavated deep horizons of soil (EDH); (b) crushed concrete (CC, 40–80 mm fraction); (c) green waste compost (GWC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the beginning of the experiment (May 2013), samples of topsoil (0–20 cm) were taken from the centre of each plot before tree planting. The physical and chemical analyses were made in the fraction of soil < 2 mm which is the fraction of soil volume exploitable by roots and macrofauna. Therefore, blocks of concrete, which can be considered inert during the three-year survey, and some residuals of wood from compost were not included. Granulometry without decarbonation (coarse: 2 mm – 50 μm, medium: 2 μm – 50 μm, and fine < 2 μm, NFX 31–107), pH (1:5 soil: water suspension, NF ISO 10390), cation exchange capacity (CEC, Metson NFX 31–130), available phosphorous (P_2O_5, Olsen NF ISO 11263) and exchangeable potassium (K_2O, water extraction 1/5 and ICP AES dosage NF ISO 10390) were measured by a soil analysis laboratory, SADEF (Aspach-le-Bas, France). Furthermore, the concentrations of five trace metals potentially present (Cu, Pb, Ni, Zn and Cd) in green waste compost (Beesley and Dickinson, 2010), amended urban soils (Cambier et al., 2019) and construction and demolition wastes (Gao et al., 2015) were measured, as well as, soil organic carbon (SOC, $g.kg^{-1}$, gas chromatography) and total nitrogen (NT, $g.kg^{-1}$, gas chromatography) at the analytical platform Alysés (IRD & Sorbonne Université, Bondy, France).

2.4. Tree planting

In December 2013, six tree species were planted: field maple (*Acer campestre* L.), Norway maple (*Acer platanoides* L.), sycamore maple (*Acer pseudoplatanus* L.), European hornbeam (*Carpinus betulus* L.), wild cherry (*Prunus avium* L.) and Small-leaved lime (*Tilia cordata* Mill.). As one of the objectives of the study was to identify tolerant species, we chose to screen several ones. However, due to space and budgetary constraints, only one individual of six different tree species was planted in each plot. All species were planted in same position in the 12 plots (Fig. 1c, $N = 72$ trees, $n = 3$ per Technosols). All trees were bought from the Pépinières-Chatelain nursery (Le Thillay, France), were between six to eight years old at the time of planting and had a trunk diameter at breast height ranging from 3.5 to 5.1 cm. The trees were planted bare root in order to measure the direct impact of the different types of constructed Technosols on the survival and growth of trees. Holes around the trees were filled with the same materials used in the plot, except for the plots with Crushed Concrete mixtures, where only Excavated Deep Horizons was used, in order to avoid root damage. The soil matric potential (-kPa) was monitored from April to September during the first two years of growth, in order to identify critical moments when watering were needed. The survey was carried out by the engineering consultancy Hydrasol around two species among the six species, *Acer platanoides* and *Carpinus betulus*. Three tensiometers (Watermark®) were placed at 0.2 m from root collar and 0.25 m of depth (P1); 1 m from root collar and 0.25 m of depth (P2); and 1 m from root collar and 0.75 m of depth (P3). Trees were irrigated when values of soil matric potential were fallen to −150 kPa. Data are presented in Fig. A in Appendix.

2.5. Survival and growth survey of trees

The survival and growth of trees were monitored each February over three years before bud break and regrowth. Trees without any new leave or bud during the monitoring period for two successive years were considered to be dead. Dead trees in plots were left in place in order to avoid potentially higher disturbances caused by their removal for the neighbouring trees and the soil fauna than the changes associated with the presence of dead roots. The three measurements of growth: (1) height, (2) trunk circumference and (3) length of five marked axillary branches since the first monitoring in 2014, were measured directly with rods and tape. The trunk circumference was measured at 1.30 m and divided by Π in order to obtain the diameter at breast height (DBH), a standard method. The axillary branches were randomly chosen at the beginning of the experiment.

2.6. Macrofaunal sampling and identification

Soil invertebrates with a body length > 2 mm were sampled by a method adapted from the Tropical Soil Biodiversity and Fertility program (TSBF) (Anderson et al., 1993). After the setting up of the plots in 2013, one sample at the centre of each plot was taken. The colonization potential of the constructed Technosols by macro-invertebrates was thus evaluated by analysing the density ($individuals.m^{-2}$) and taxonomic richness ($number\ of\ taxa.quadrat^{-1}$) the three years after the plots were established. Three quadrats of 25 cm × 25 cm were placed lengthways along the centre of the plots and were spaced by three meters (Fig. 1c). To avoid sampling in the same location, the quadrats were moved by 1 m each year. In order to determine the local pool of macro-invertebrates susceptible to recolonize our plots, three surrounding locations, each replicated three times, were also sampled each year (Fig. 1d). The first sampling step consisted in applying Formalin (0.4% dilution) to the quadrats. All the organisms that emerged from the soil during the 10 subsequent minutes were then collected. This was repeated twice at each sampling point. Finally, soil was excavated to a depth of 20 cm and hand-sorted to retrieve the rest of the macrofauna. The organisms were identified to the class (Diplopoda, Chilopoda), order (Araneae, Dermaptera, Hemiptera, Isopoda, Lepidoptera larva, Mecoptera larva and Opiliones) and family levels (Aphididae, Formicidae, Lumbricidae, and Coleoptera adults and larva, and Diptera larva). Shell and no-shell terrestrial gastropods were gathered as snails and slugs respectively.

2.7. Statistical analyses

The survival of trees was analysed using a generalized linear regression (binomial family) with the R packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017). The tested factors were the duration since plantation, the type of constructed Technosols and the tree species. To compare significance of factors, an analysis of deviance was performed using the chi-squared test. To study the growth of the trees, height, diameter and length of each axillary branch were considered as response variables in linear mixed models. The size of axillary branches was log-transformed to ensure a normal distribution of residuals. However, the raw data were presented on Fig. 3c, and the equation of the log-linear model was transformed to the antilog expression. The fixed effects were the age after plantation and the type of constructed Technosols. For the tree growth analyses, the species effect could not be tested because there were insufficient numbers of replicates, due to the mortality of trees during the three-year experiment. The species effect was set as a random effect on slope and intercept with time. The best fitting models were chosen comparing Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). Because of differences of height, diameter and size of axillary branches at the beginning of the survey, the intercepts of the first year of the survey were not compared between treatments. The slopes of linear regressions were estimated by restricted maximum likelihood (REML) and compared between Technosols with analyses of variance. Differences in soil characteristics, abundance and taxonomic richness of macrofauna in Technosols were analysed by ANOVA and post-hoc Tukey test (package Agricolae; De Mendiburu, 2017), after checking normal distribution of residuals with the Shapiro-Wilk's test, and homoscedasticity with the Bartlett's test. All statistical analyses were performed with R software version 3.4.3 (R Core Team, 2017) and RStudio version 3.4.1 (RStudio Team, 2016).

3. Results

3.1. Survival and growth of trees in constructed Technosols

The survival of trees after three years varied among species ($P < 0.001$), in the following order: *Acer campestre* and *Prunus avium*

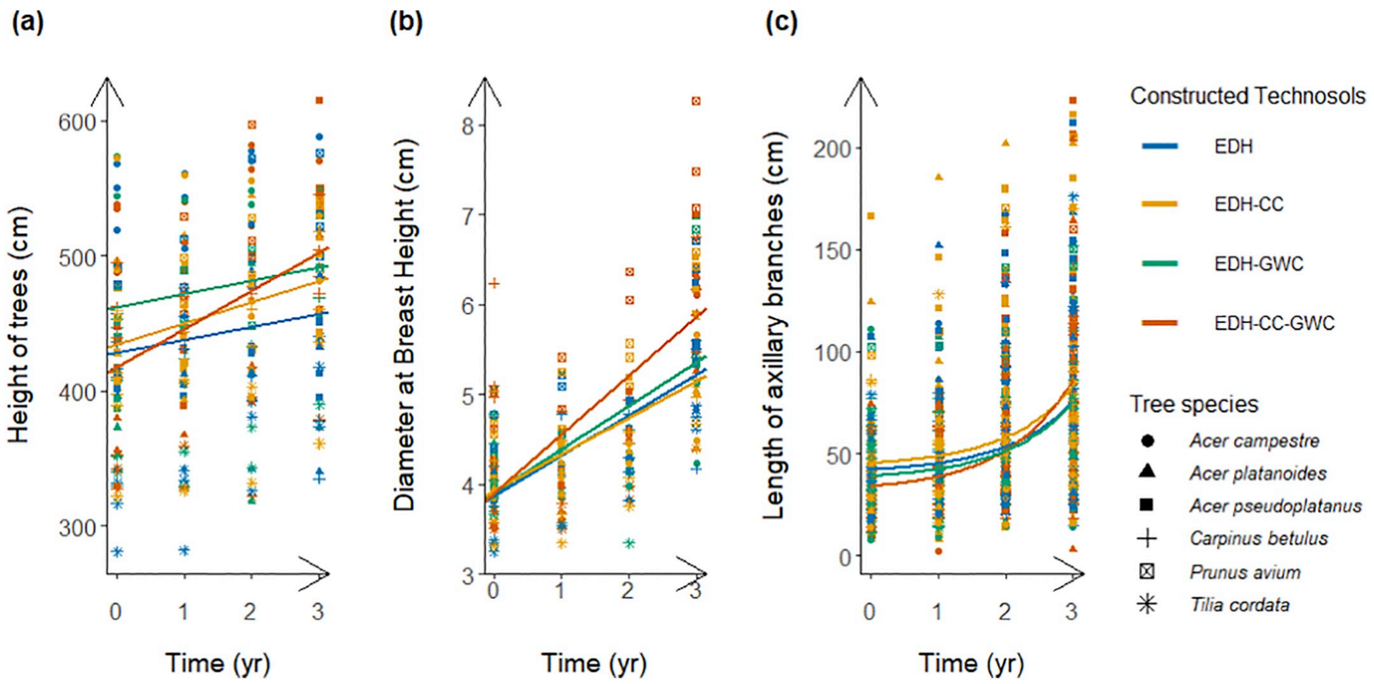

Fig. 3. Tree growth of the different species in four constructed Technosols. Evolution of height (a), circumferences of trunk (b) and length of axillary branches (c) of trees in function of time. Constructed Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost). Shapes represent tree species, and lines illustrate regressions for each soil ($n = 3$ per Technosols and tree species). All linear regressions had an estimated parameter of slope significantly different from zero (p-value < 0.05; see Table 2). Despite the log-linear regression applied to growth of axillary branches, we presented raw data and the antilog curves for an easier reading. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Comparison of tree growth parameters in four different Technosols (linear mixed-effect models).

	Height	Diameter at Breast	Length growth of axillary branches	
	$y = Ax + B$	$y = Ax + B$	$y = BA^t$	
Technosols	A	A	A	B
EDH	9.52 ± 4.11 a	0.44 ± 0.07 a	1.24 ± 1.07 a	32.7 ± 1.16 a
EDH-GWC	9.57 ± 6.48 a	0.41 ± 0.08 a	1.21 ± 1.06 a	31.7 ± 1.16 a
EDH-CC	15.46 ± 5.88 a	0.49 ± 0.07 ab	1.29 ± 1.05 ab	33.3 ± 1.16 a
EDH-CC-GWC	28.34 ± 5.88 b	0.65 ± 0.07 b	1.39 ± 1.05 b	26.2 ± 1.16 a

Means ± standard errors; letters (a, b) indicate significant differences ($P < 0.05$); $n = 3$. Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost)

(100%), *Acer platanoides* (83%), *Acer pseudoplatanus* and *Tilia cordata* (75%), *Carpinus betulus* (58%). Tree death occurred mainly during the first year after planting (time effect, $P < 0.01$; Table 1). The rate of survival of all species was highest in pure Excavated Deep Horizons (EDH; 94%) and was lowest in Excavated Deep Horizons with Green Waste Compost (EDH-GWC; 56%, 10/18 dead trees in total; $P < 0.001$), especially with the loss of all *Acer pseudoplatanus*. It was intermediate in the other Technosols: Excavated Deep Horizons with Crushed Concrete (EDH-CC, 89%) and Excavated Deep Horizons with Crushed Concrete and Green Waste Compost (EDH-CC-GWC, 89%). Tree height and diameter increased linearly (Fig. 3a and b; Table 2), whereas the axillary branches displayed an exponential growth (Fig. 3c; Table 2). The height growth rate was significantly faster in EDH-CC-GWC as compared with EDH, EDH-CC and EDH-GWC treatments ($P < 0.01$; Table 2). The increase of the diameter was 32% higher in EDH-CC-GWC than in EDH and EDH-GWC ($P < 0.05$). Concerning the growth of axillary branches, the parameter A associated with time in the equation describing this growth (Table 2) was significantly higher for EDH-CC-GWC than EDH and EDH-GWC (respectively, 25% and 40% more, $P < 0.05$). However, this parameter was not significantly different from EDH-CC treatments.

3.2. *Abundance and taxonomic richness of soil macrofauna*

In 2013, directly after the establishment of the plots, we did not find any macrofauna invertebrate in the constructed Technosols. Three years after, the macrofauna abundance had increased in all Technosols (Fig. 4a) and did not differ significantly from the local surrounding abundance of macro-invertebrates (1205 ± 113 ind.m^{-2}). The macrofaunal abundance was twice higher in EDH-CC-GWC than in EDH and EDH-CC Technosols, with a value of 1618 ± 113 ind.m^{-2} against 887 ± 154 ind.m^{-2} on average ($P < 0.01$). There was no differences in taxonomic richness between Technosols (10.3 ± 0.2 taxa.quadrat^{-1}) and with the local pool after three years of experiment (10.6 ± 0.9 taxa.quadrat^{-1}; Fig. 4b). The colonization or reproduction were higher in EDH-CC-GWC than in other treatments. After one year of experiment, there was no significant difference between the first treatment with surrounding in abundance and taxonomic richness of

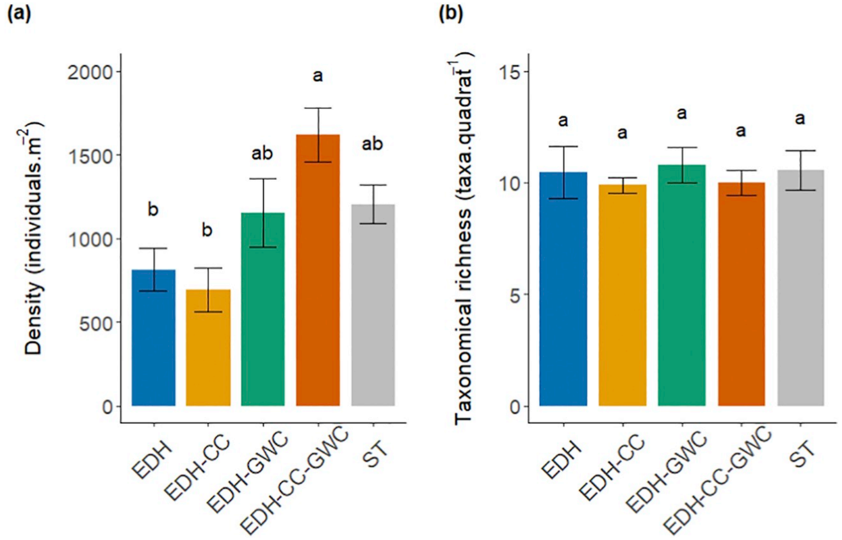

Fig. 4. (a) Density (individuals.m^{-2}) of macrofauna by quadrat after three years of experiment; (b) Taxonomic richness (taxa.quadrat^{-1}). Constructed Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost); ST: surrounding topsoil to determine the local pool of macroinvertebrates. Results expressed as means ± standard errors (n = 3); letters (a, b) indicate significant differences between constructed Technosols ($P < 0.05$) three years after the setting up. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

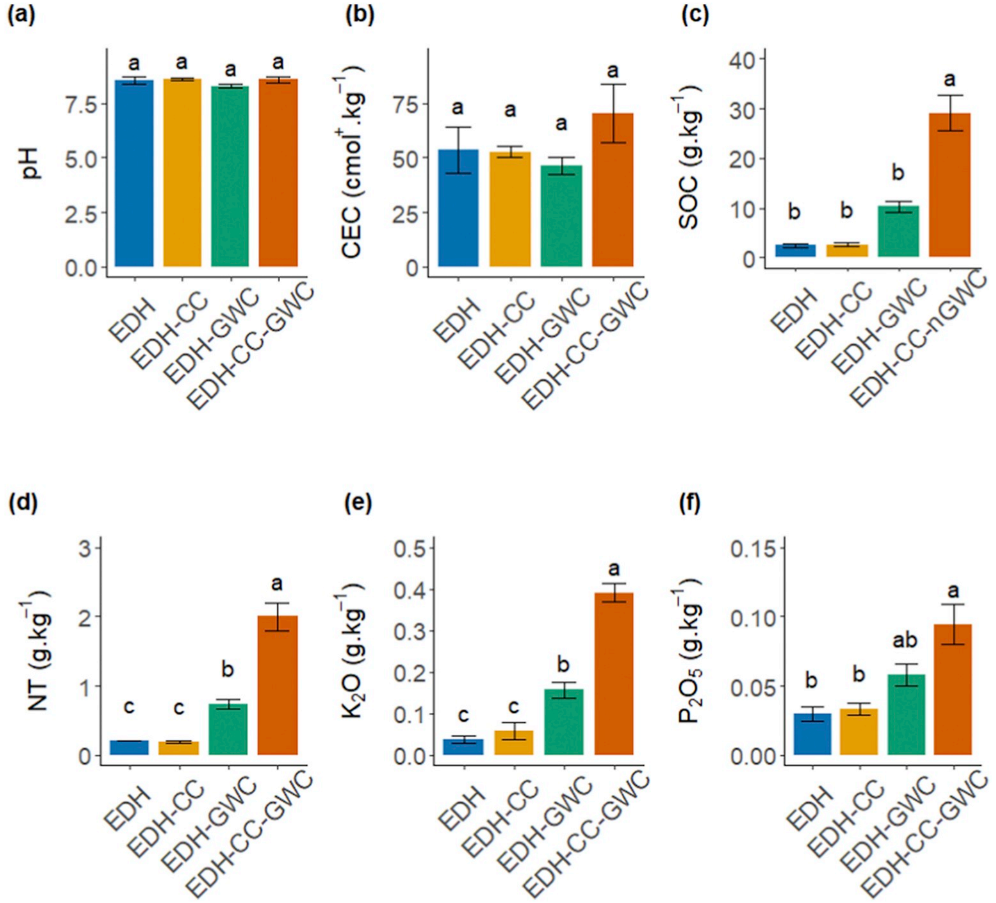

Fig. 5. (a) pH water; (b) Cation Exchange Capacity (CEC, cmol$^+$.kg^{-1}); (c) Soil Organic Carbon (SOC, g.kg^{-1}); (d) Total nitrogen (NT, g.kg^{-1}); (f) Exchangeable potassium (K_2O; g.kg^{-1}) (e) Available phosphorous (P_2O_5; g.kg^{-1}). Analyses were performed on the fraction < 2 mm, which excludes concrete blocks, considered as inert material over the three-year experiment. Constructed Technosols: EDH (100% of excavated deep horizons of soil); EDH-GWC (90% of excavated deep horizons of soil, 10% of green waste compost); EDH-CC (30% of excavated deep horizons of soil, 70% of crushed concrete); EDH-CC-GWC (20% of excavated deep horizons of soil, 70% of crushed concrete, 10% of green waste compost). Results expressed on dry matter, as means ± standard errors (n = 3); letters (a, b, c) indicate significant differences between constructed Technosols ($P < 0.05$) at the beginning of experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

soil macrofauna.

3.3. Physical and chemical characteristics of constructed Technosols

At the beginning of experiment, the particle size distribution of the fraction (< 2 mm), excluding blocks of concrete was similar among Technosols. In this soil granulometry fraction, the coarsest and medium size classes (2 mm – 50 µm and 50 µm – 2 µm), which accounted for the large majority of the particles, did not present any significant difference between treatments (682 ± 12 g.kg^{-1} and 200 ± 11 g.kg^{-1} on average, respectively). Only the amount of finest particles (< 2 µm) in EDH-CC (84 ± 17 g.kg^{-1}) was significantly lower than in EDH (139 ± 5 g.kg^{-1}). There were no other significant differences (107 ± 12 g.kg^{-1} in EDH-GWC and 95 ± 4 g.kg^{-1} in EDH-CC-GWC). The pH and CEC of different soils were not significantly different and equal to 8.5 ± 0.1 and 55.8 ± 5.1 cmol$^+$.kg^{-1} on average, respectively (Fig. 5a and b). The organic carbon content in EDH-CC-GWC Technosols was 29.17 ± 3.47 g.kg^{-1} (Fig. 5c); this was ten times more ($P < 0.001$) than in EDH and EDH-CC (2.48 ± 0.32 g.kg^{-1} and 2.61 ± 0.33 g.kg^{-1}, respectively) and three times more ($P < 0.001$)

Table 3

Annually growth rate of the height (cm.yr^{-1}), the trunk circumference (cm.yr^{-1}) and random axillary branches (cm.yr^{-1}) from various studies.

Species	References	Location	Environment	Mean annual growth rate (cm.yr^{-1})		
				Height	Diameter at Breast Height	Length of axillary branches
Acer campestre	Sjöman et al., 2012	Romania and Moldova	Forest with urban hydric stress	26 ± 0.08	0.28 ± 0.08	
Carpinus betulus	Sjöman et al., 2012	Romania and Moldova	Forest with urban hydric stress	29 ± 0.07	0.30 ± 0.07	
Acer platanoïdes	Solfjeld and Hansen, 2004	Norway	Field			37 ± 12.5[b]
Acer spp.	McPherson et al., 1994	Chicago, USA	Urban	15	0.80	
Acer pseudoplatanus	Vaz Monteiro et al., 2017	Great Britain	Urban	35 ± 0.04	0.92 ± 0.08	
Prunus avium	Levinsson et al., 2017	Sweden	Urban			18.37 ± 13.70
	Solfjeld and Hansen, 2004	Norway	Field			23 ± 13.2[b]
	Loewe M. et al., 2013	Chile	Urban	39 ± 17[c]	0.77 ± 0.27[c]	
Tilia cordata	Moser et al., 2015	Germany	Urban	20 ± 1[a]	0.72 ± 0.04[a]	
Tilia × europea (hybrid between Tilia cordata and *Tilia platyphyllos*)	Solfjeld and Hansen, 2004	Norway	Field			60.7 ± 6.8[b]

Means ± standard errors.

[a] Dividing by the age of the tree control.

[b] Mean of annually shoot increments of tree controls for three years experiment.

[c] Slope calculated from fitted curve.

than in mixtures EDH-GWC (10.32 ± 1.13 g.kg^{-1}). The same pattern was observed for the total nitrogen content (Fig. 5d), with the highest value for EDH-CC-GWC (2.00 ± 0.20 g.kg^{-1}), then EDH-GWC (0.74 ± 0.07 g.kg^{-1}) followed by EDH and EDH-CC (respectively 0.21 ± 0.004 g.kg^{-1} and 0.19 ± 0.02 g.kg^{-1}). The C/N ratios ranged from 11.80 (EDH) to 14.59 (EDH-CC-GWC) with no significant difference. The available phosphorous concentration (Fig. 5e) was significantly higher ($P < 0.01$) in EDH-CC-GWC (0.09 ± 0.01 g.kg^{-1}) than in EDH and EDH-CC (0.03 ± 0.01 g.kg^{-1} on average), with an intermediate value for EDH-GWC (0.06 ± 0.01 g.kg^{-1}). The exchangeable potassium concentration (Fig. 5f) was eight times higher in EDH-CC-GWC (0.39 ± 0.02 g.kg^{-1}) and three times higher in EDH-GWC (0.16 ± 0.02 g.kg^{-1}; $P < 0.05$) than in EDH and EDH-CC (0.04 ± 0.01 g.kg^{-1} and 0.06 ± 0.02 g.kg^{-1} respectively). The total Cd concentrations were lower than the detection threshold of the measuring instrument (i.e. 6 mg.kg^{-1}; Fig. B in Appendix). The total Pb concentrations were not significantly different among treatments and equal to 36.4 ± 0.41 mg.kg^{-1}, on average. These concentrations are lower than the maximal reference threshold, defined as the maximal value which could occur naturally, in Ile-de-France region (Mathieu et al., 2008; Foti et al., 2017) which is equal to 53.7 mg.kg^{-1}, and lower than the maximum authorised concentration in sewage sludge spreading on agricultural soil defined by the French decree (n°97–1133 1997-12-08) and the European Directive 86/278/EEC which is 100 mg.kg^{-1}. The total Ni concentrations were inferior to detection threshold of measuring instrument (12 mg.kg^{-1}) in all plots, except in the third plot of EDH-CC-GWC (25.8 mg.kg^{-1}) and lower than the reference in Île-de-France region (31.2 mg.kg^{-1}) and the maximum authorised concentration for muckspreading of sewage sludge (50 mg.kg^{-1}). The total Cu concentrations of all plot were lower than the reference in Île-de-France region (28.0 mg.kg^{-1}) except in the third plot of EDH-CC-GWC (82.35 mg.kg^{-1}), but lower than the reference for muckspreading of sewage sludge (100 mg.kg^{-1}). The total Zn concentrations of all plots were lower than the reference in Île-de-France region (88.0 mg.kg^{-1}) except in the third plot of EDH-CC-GWC (117.4 mg.kg^{-1}), but lower than the reference for muckspreading of sewage sludge (300 mg.kg^{-1}).

4. Discussion

4.1. Physical and chemical properties of Technosols

The choice of materials was made based on their individual physico-chemical properties, but the properties of the mixes of materials was difficult to predict as many characteristics are not additive (Rokia et al., 2014). Because analyses were performed on the Technosol fraction < 2 mm to avoid taking into account inert concrete composition, the addition of crushed concrete and green waste compost only had a small effect on the texture of the Technosols. Since all parent materials had similar pH values, no differences among the four treatments were observed, as expected. The alkaline pH of these constructed Technosols was comparable to most urban soils (Lehmann and Stahr, 2007). The increase in the organic matter content of the Technosols amended with compost had no significant effect on CEC but improved the availability of nutrients -such as phosphorous and potassium- for plants. Although Technosols composed of Excavated Deep Horizons and Green Waste Compost (EDH-GWC), and Excavated Deep Horizons, Crushed Concrete and Green Waste Compost (EDH-CC-GWC) had the same initial proportion of compost, the addition of crushed concrete (70% of the total) led to an increase in the concentration of the organic matter in the fraction of the soil volume exploitable by roots. In this soil volume the ratio of EDH: Green Waste Compost in EDH-GWC was 9:1, while in the EDH-CC-GWC mixture it was 3:1. The higher organic matter concentration also lead to higher available potassium (x 2.4) and available phosphorus (x 1.5). The presence of high total Ni, Cu and Zn values in a single sample in one EDH-CC-GWC plot (Fig. B in Appendix) may be due to the presence of a metallic artefact in the mixtures, revealing the importance of parent material selection for the construction of Technosols. The overall low trace element values suggest that the pollution risk associated with the use of this type of constructed Technosol for urban greening is low.

4.2. Constructed Technosols as potential planting substrates for urban trees

Overall the different tree species succeeded in growing in the Technosols; only *Carpinus betulus,* in all treatments, and *Acer pseudoplatanus*, in Excavated Deep Horizons with Green Waste Compost (EDH-GWC) had limited survival. However, the total annual tree mortality rate of 6% found here was above the 1.6 to 5.1% mortality rate found in other tree planting studies in urban environments (Roman and Scatena, 2011; Roman et al., 2014, 2015). A chief reason for this difference may be the fact that in our experiment the trees were planted with bare roots, which is known to increase tree mortality. The literature (Table 3) indicates that the annual diameter growth rates range from 0.28 ± 0.08 $cm.yr^{-1}$ for *Acer campestre* (Sjöman et al., 2012) to 0.92 ± 0.08 $cm.yr^{-1}$ for *Acer pseudoplatanus* (Vaz Monteiro et al., 2017), which is similar to the values we found in the different Technosols. Tree height growth was found to range from 17 $cm.yr^{-1}$ for *Acer spp.* (McPherson et al., 1994) to 39 ± 17 $cm.yr^{-1}$ for *Prunus avium* (Loewe et al., 2013). These values are similar to the ones we found on average for all species in Excavated Deep Horizons with Crushed Concrete (EDH-CC; 15.46 ± 5.88 $cm.y^{-1}$) and Excavated Deep Horizons with Crushed Concrete and Green Waste Compost (EDH-CC-GWC; 28.34 ± 5.88 $cm.y^{-1}$, but higher than what we found in control (EDH;9.52 ± 4.11 $cm.y^{-1}$) and Excavated Deep Horizons with Green Waste Compost (EDH-GWC; 9.57 ± 6.48 $cm.y^{-1}$).

We expected higher survival and growth rates of trees as plant nutrient availability or of organic matter content increased and a negative effect of crushed concrete. However, this was not the case. There was no impact of the crushed concrete addition, while the 10%-addition of compost surprisingly increased the mortality compared to other survival and growth studies of urban trees (Layman et al., 2016). There are three possible explanations for the negative effect of compost in the EDH-GWC treatment. First, increased mortality or reduced growth rate in the presence of compost has been attributed to phytotoxic and inhibiting compounds of growth in unstable green waste compost (Sæbø and Ferrini, 2006). However, this was not relevant here since any putative phytotoxins would have been more concentrated in EDH-CC-GWC than in EDH-GWC because the concentration of compost in the volume exploitable by roots was higher in the EDH-CC-GWC treatment. A second possible explanation is that the organic matter added to the compost treatments stimulated microbial activity to such an extent that there was a reduction in oxygen levels in the soil, resulting in an asphyxiation of the plant roots (Drew and Lynch, 1980). The crushed concrete might have ensured a higher porosity and mitigated this phenomenon. However, anaerobic conditions occur under specific conditions such as compaction (Day et al., 1995), waterlogging (Drew and Lynch, 1980), which did not occur in this experiment. The third possible explanation for the negative effect of green waste compost in the absence of crushed concrete is related to water availability. Although compost is known to increase the water retention capacity of Technosols (Deeb et al., 2016b; Yilmaz et al., 2018), the preparation of the constructed Technosols may have resulted in a lowering of water infiltration. The mechanical mixing of the materials when setting up the experimental plots was carried out in wet weather. This could have led to particle sorting and favoured the deposition of finer particles at the soil surface, which favours soil crusting (Valentin and Bresson, 1992). The sealing of soil surface may have reduced water infiltration and resulted in a lower water contents in the EDH-GWC treatment relative to the other treatments. However, the water potential in EDH-GWC plots did not raise values below −150 kPa more frequently or during longer periods, than in other Technosols (Fig. A in Appendix). There was more water and probably less soil crusting in EDH because there was only one component and thus no need to mix. In EDH-CC-GWC, mixing could have led to the same crusting, but the roughness of soil surface due to the presence of concrete may have limited this effect. It would be necessary to carry out surface infiltration measurements to verify this hypothesis.

4.3. Colonization of Technosols by soil macrofauna

After three years, soil macrofauna colonized the four Technosols up to similar density and diversity to the neighbouring woods and meadows. The macrofauna density in constructed Technosols was in the same range to less disturbed meadows in the North West region of France (678 ± 355 $ind.m^{-2}$, Cluzeau et al., 2012), and in others constructed Technosols (1044 to 619 $ind.m^{-2}$, Hedde et al., 2019). The diversity was similar to constructed soils with non-hazardous construction and demolition wastes (11.6 ± 4 family groups, Vincent et al., 2018). Hedde et al. (2019) and Mathieu et al. (2005) found similar rapid colonization of respectively a constructed Technosols in a rural landscape of France and of deforested plots by soil macrofauna in Amazonia respectively.

All Technosols hosted similar soil macrofauna diversity, but with higher abundance in the presence of both crushed concrete and compost (EDH-CC-GWC) that in pure EDH or in EDH-CC. Macrofaunal density was higher with the addition of compost, which led to higher organic matter content, nitrogen, potassium and phosphorous. Vincent et al. (2018) found similar results with a positive correlation between higher potassium, organic matter contents, or herbaceous plant biomass with density and diversity of macrofauna in constructed and non-constructed Technosols. Tree growth was not correlated to the density of macrofauna (result not shown), conversely to observed correlations between soil fauna (macrofauna and mesofauna) communities and tree growth in Belgian beechwood on natural soils (Ponge et al., 1997). Plots with only 70% crushed concrete addition (EDH-CC) presented intermediate growth rates of trees, but lowest density of macrofauna, while plots with 10% of green waste compost addition (EDH-GWC) presented lowest tree survival and growth and intermediate values of macrofauna density. These results suggested that green waste compost addition in initial mixture, which induced enhanced soil fertility and faster growth of trees, constitutes the main driver of macrofaunal abundance in constructed Technosols. Furthermore, the experiments of Pey et al. (2014) and Deeb et al. (2017) demonstrated that green waste compost addition in Technosols enhanced activities of earthworms and led to increase the mixing of organic and mineral particles, and the aggregate stability, which is determinant for evolution and functioning of constructed Technosols.

We cannot determine if abundance was related to colonization or reproduction. However, previous studies have shown that in extreme conditions of dispersal in urbanized areas, such as green roofs, the lack of soil fauna colonization (earthworms and microarthropods) hardly reduced soil functioning and ecosystem service delivery (Rumble and Gange, 2013; Grard et al., 2018). Burrow (2018) demonstrated that connectivity of constructed Technosols thanks to corridors was critical for earthworms and collembolans colonization.

5. Conclusion and perspectives

This study shows that it is possible to grow trees in soils constructed from urban construction and demolition wastes. Excavated deep horizons of soils are a relatively good substratum for tree survival, but do not offer optimal tree growth without addition of crushed concrete and green waste compost. The best substratum was the mix between excavated deep horizons, crushed concrete and green waste compost, in which good results were obtained for both survival (89%) and growth (Fig. 3, Table 2). Among the six-tree species tested in our experiment, *Carpinus betulus* was not adapted to the different Technosols whereas

Acer campestre and *Prunus avium* were very well adapted (100% of survival), with intermediate survival rate for the other species (*Acer platanoides*, *Acer pseudoplatanus* and *Tilia cordata*). It is thus necessary to choose the species carefully as their survival rates can differ quite dramatically. Even though our experiment lasted three years, it is essential to monitor the evolution of soil fertility and trees growth over a longer period of time. More particularly, the consequences of the dissolution and fragmentation of concrete materials on the physical, chemical and biological properties of the Technosols need to be assessed. The nature of our constructed Technosols allowed macrofauna colonization. It would be interesting to measure macrofauna colonization and reproduction in constructed Technosols in dense areas where urban barriers to dispersal are likely more influent. Overall, this study Foti et al., 2017 suggests that recycling urban construction and demolition wastes is a suitable alternative to importing natural soil. It may help satisfy the demand for soil for landscaping purposes in urban areas while avoiding the exploitation of natural soils.

Glossary

Constructed Technosols: these soils are typically made for specific functions, such as vegetation support (Séré et al., 2008). They contain at least 20% material created or modified by human activities (industrial or artisanal), such as garbage, industrial waste, glass, pottery or bricks (IUSS Working Group WRB, 2014).

Construction and Demolition wastes: leftovers from the construction or demolition of concrete structures, masonry, roadbeds, asphalt pavements, rubble or excavated soils (EU List of Wastes 2000/532/EC).

Crushed concrete: concrete made of slabs and pillars of building foundations that were crushed and sieved after the removal of iron pieces.

Excavated Deep Horizons of soil: excavated subsoil made up of soil from the C horizon (approximately 95%), the remaining being all types of materials from deconstruction sites (crushed tile, tiles, brisk…) that were not correctly sorted.

Green waste compost: compost produced from turf grass mowings and trimmings from trees and shrubs.

Urban greening: the introduction, conversion or maintenance of outdoor vegetation in urban areas in order to improve urban environmental conditions for inhabitants (Kuchelmeister, 1998; Eisenman, 2016).

Declaration of Competing Interest

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Appendix A. Supplementary data

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