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Original article – Thematic Issue

Effect of organic amendment for the construction of favourable urban soils for tree growth

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Summary

Ornamental tree planting and establishment in cities is a great challenge because urban soil physical properties are unfavourable to the development of root systems. Our objectives were to measure (i) the effects of organic matter on soil physical properties and tree development, and (ii) the effects of ensuing root development on soil physical properties. Using twenty-four 600-L planted or bare soil containers, we monitored physical properties such as dry bulk density, aggregate stability and near-saturated hydraulic conductivity of our reconstituted soils over a 5.5-year period. A 28-cm thick top layer of sandy loam amended with 40% (v/v) *sphagnum* peat or organic composts was laid on top of a 28-cm thick layer of sandy loam. Bare-root *Ostrya carpinifolia* trees were planted in half of the 24 containers, and we monitored shoot development and root biomass and distribution. After 5.5 years, trunk diameter had increased from 59 mm for the control soil to 66 mm for soil mixed with green waste compost, and 74 mm for soil mixed with co-compost of sewage sludge and wood chips. After 4.5 years, trunk diameter was strongly correlated with the total number of axes (r = 0.94) and fine root length density (r = 0.98), and was confirmed as a good indicator of tree development. Fine root development increased stable aggregate formation in all treatments as compared to bare soil. After 4.5 years after planting, the tree root system induced by a high organic matter input had significantly improved near-saturated hydraulic conductivity and was fit to support fertile urban soils.

Keywords
aggregation, artificial soil, compost, *Ostrya carpinifolia*, tree development, urban horticulture

Significance of this study

What is already known on this subject?

- The quality of the constructed soil used for backfilling the tree pit plays a major role in tree performance. Soil organic matter content also plays a key role in agronomic fertility, so the use of organic amendments and especially composts appears as an ideal solution to boost urban tree growth.

What are the new findings?

- The addition of high levels of organic composts immediately improved the soil physical properties (e.g., dry bulk density, aggregate stability and hydraulic conductivity) and in return fine tree roots modified soil structure and decreased dry bulk density in the top layer. Correlation coefficients confirmed trunk diameter as a very good indicator of tree above and belowground architecture.

What is the expected impact on horticulture?

- Sustainable tree planting and establishment in cities is a great challenge for managers of urban tree resources. In these cases of urban horticulture, to decrease tree replacement frequency and ensuing costs, it is necessary to improve the establishment and maintenance of trees in cities. To develop urban horticulture, it is essential to educate all the city makers (landscape architects, civil engineers, urban planners, municipal officials and urban farmers) about optimal soil specifications expected for fertile urban soils: choice of organic matter nature, sources of organic matter or mineral material, proportions of organic matter in term of soil structuring and soil profile design.

Introduction

Ornamental trees in urban areas are a major societal issue. They contribute to overall well-being through their visual effect and their impact on urban climate, and a canopy cover can help mitigate the urban heat island effect (Solecki et al., 2005). Sustainable tree planting and establishment in cities is a great challenge for managers of urban tree resources. The average lifespan of urban street trees was estimated to be only seven years (Moll, 1989) or 13 years (Skiera and Moll, 1992), with for example 39% of mortality over a five-year period after planting in Liverpool (Gilbertson and Bradshaw, 1990). Annual mortality of newly planted trees averaged 19% over a two-year period in Oakland (Nowak et al., 2004), and 10% in Finland and Iceland (Pauleit et al., 2002). Roman and Scatena (2011) conducted a meta-analysis of US studies on the survival of urban trees. They showed that the average lifespan was actually longer (19 to 28 years) than specified in previous studies (7 to 13 years). In all cases, to decrease tree replacement frequency and ensuing costs, it is necessary to improve the establishment and maintenance of trees in cities. The reduction of annual urban tree mortality during the first years after planting depends on (i) quick root system development to promote efficient water and nutrient uptake; (ii) quick recovery of aerial growth and elongation of annual shoots; and (iii) restoration of 'normal' root architecture, modified by nursery preparation, for the different types of roots: anchor, exploration and colonization as reviewed in Atger and Edelin (1994) and Day et al. (2010).

Urban conditions are unfavourable to the development of good root system architecture due to small volumes and compacted, heterogeneous and often sterile materials in the soils (Jim, 1998; Pouyat et al., 2007). In urban soils, high bulk density decreases root penetration depth (Zisa et al., 1980), and restricted rooting areas can result in reduced total root surface areas (Day and Bassuk, 1994). Specifications for topsoil for tree planting have been developed by planners or civil engineers, but they are often inappropriate (Bartens et al., 2008). In the early 1990s, the standard of CU-structural soil™ developed at Cornell University (Grabosky et al., 2002) for tree planting was proposed to improve tree-available soil volume and play a supporting role for pavements (Bartens et al., 2008). The quality of the constructed soil used for backfilling the tree pit plays a major role in tree performance (MacDonald et al., 2004). But assessing urban soil quality is really difficult and depends on urban uses and needs. Soil physical properties such as dry bulk density, textural composition, infiltration rate or aggregate stability have been proposed as major quality indicators of urban tree growth (Jim, 1998; Hanks and Lewandowski, 2003; Vrscaj et al., 2008; Scharenbroch and Catania, 2012). Soil organic matter content plays also a key role in agronomic fertility, so the use of organic amendments and especially composts appears as an ideal solution to boost urban tree growth (De Lucia et al., 2013). The effects of exogenous organic matter in soils has been studied by many authors who observed (i) the increase of aggregate formation and of structural stability (Angers et al., 1999; Chenu et al., 2000); (ii) the improvement of soil water retention (Rawls et al., 2003; Celik et al., 2004) and saturated hydraulic conductivity (McCoy, 1998; Aggelides and Londra, 2000; Vidal-Beaudet et al., 2009); (iii) the increase of soil porosity (Marinari et al., 2000; Zeytin and Baran, 2003) and of the resistance to compaction (Zhang et al., 1997; Vidal-Beaudet and Charpentier, 2000); and (iv) the increase of available nutrients for plant growth (Smith et al., 2010; De Lucia et al., 2013) and of the tree performance (root length density, uniform distribution of roots) (Smith et al., 2010). These studies were in general carried out for small additions of organic matter – less than 10 g of C per kg of total soil dry mass (Annabi, 2005) – corresponding to classical agricultural practices. Urban practices are an example of addition of large quantities of organic matter to the soil in a single dose and C contributions may be as high as 50 g per kg of total soil dry mass. Incorporating a great quantity of organic matter at 40% (v/v) into the first 30 cm of an urban constructed soil or to amending tree planting holes is a traditional practice (Day and Bassuk, 1994) which improved soil physical properties and soil structuring by enhancing aggregation (Grosbellet et al., 2011).

Good physical, chemical and biological properties influence on plant growth and microorganism activity, and in return soil properties are modified by the roots and the soil fauna (Angers and Caron, 1998; Gregory, 2006). The physical changes induced by roots are presently understudied as compared to chemical and biological changes (Gregory and Hinsinger, 1999). As chemical binding, microbial activity, earthworms, roots have a major influence on soil formation and aggregation (Tisdall and Oades, 1982). They release carbon compounds, source substrates and energy for microorganisms which produce microbial polysaccharides that promote the formation of water-stable macro-aggregates (>250 µm diameter) (Angers and Caron, 1998). Aggregation depends on the amount of fungal hyphae and roots in the soil (Tisdall and Oades, 1982). Tree roots also increase macroporosity and saturated hydraulic conductivity (Ksat) of compacted soils (Yunusa et al., 2002; Bartens et al., 2008). By growing into the soil, roots change the soil structure through the formation of continuous macropores (>30 µm diameter) (Angers and Caron, 1998; Lesturgez et al., 2004). These macropores facilitate aeration, water movement, and growth of future roots. Root-soil interactions have been studied on annual crops in agricultural soils, but far less on perennial trees in urban soils. The processes induced by roots in urban soils need to be further studied by assessing the effects of tree root growth on the maintenance of good agronomic properties over a long period under urban conditions.

We hypothesized, by ignoring deliberately the role of microorganisms and other chemical or physical parameters, that the roots of *Ostrya carpinifolia* could significantly improve soil physical properties (i.e., bulk density, structural stability and near-saturated hydraulic conductivity) of urban constructed soil. The objectives of this study were to determine (i) the effects of the addition of a great quantity (40% v/v) of organic matter on soil physical properties and aboveground and belowground tree development, and in return (ii) the effects of root development on soil physical properties over 5.5 years.

Materials and methods

Material characterization and experimental set-up

The soil material (0–30 cm) was collected from a cultivated surface horizon located near Angers (47°28'N, 00°36'W), north-western France. It was a sandy-loam soil composed of 32.3% fine sand (50–200 µm), 26.2% coarse sand (200–2000 µm), 28% silt, and 11.3% clay. Other properties are given in Table 1.

Different organic products were mixed with the control soil (CO) at 40% (v/v), and the mixtures were labelled SW (soil + sewage sludge/wood chip compost), GW (soil + green waste compost) and SP (soil + *sphagnum* peat). The two composts consisted of 0- to 20-mm particles that had been composted for six months and had very similar properties except for pH and total nitrogen (Table 1). The *sphagnum* peat came from Estonia. It is a very stable material currently used in urban agronomy for example in rooftop garden. All the organic products and the soil material were carbonate-free, so we considered that total carbon (C) was organic carbon. The initial physico-chemical characteristics of the three mixtures and the control are presented in Table 1. As compared to the control, increases in C content in the mixtures ranged between 22.7 g kg^{-1} for SP and 45.1 g kg^{-1} for GW. The treatments (CO, SW, GW, and SP) were applied in individual 600-L containers (1.1 × 0.9 × 0.6 m) in two layers, according to green space management practises for backfilling tree pits: the first deeper layer of 28 cm of soil was covered with a mixture top layer of 28 cm. In the control container, the soil was only sieved (20 mm). The bottom of the containers, under the deeper layer, was drained by a layer of gravel separated from the soil mass by a geotextile. Trees were planted in half of the containers. We chose *Ostrya carpinifolia* Scop. (hop hornbeam) for its weak root development and its frequent use in the city. We used clone replicates of bare-root trees of 4 m height and 12 to 14 cm trunk circumference at 1 m

Table 1. Physical and chemical characteristics of the material: sandy-loam soil, sludge/wood chip co-compost, green waste compost, and *sphagnum* peat, and treatments: control soil (CO), soil + 40% v/v sludge/wood chip co-compost (SW), soil + 40% v/v green waste compost (GW), and soil + 40% v/v *sphagnum* peat (SP).

	Particle density	Bulk density	Water pH	Total C	Total N	C/N	C from the organic product
	(g cm^{-3})			(g kg^{-1} dry mass)			(g kg^{-1} dry mass)
Sandy loam soil	2.58	1.27	6.4	7.4	1.5	4.9	–
Sludge/wood chip co-compost	1.80	0.31	6.2	253.2	25.2	10.0	–
Green waste compost	1.76	0.29	9.0	260.1	15.9	16.4	–
Sphagnum peat	1.46	0.07	4.3	484.4	13.7	35.4	–
CO	2.58	1.27	6.4	7.4	1.5	–	–
SW	2.46	1.03	6.4	47.4	4.4	–	40.0
GW	2.46	0.99	7.8	52.5	3.5	–	45.1
SP	2.53	0.98	5.3	30.1	2	–	22.7

height. Before planting, the root system was formed by large and small roots emerging diagonally from the trunk in all directions, but a main axis was visible. The trees had seven to twelve large primary structural roots that sprouted from the root collar and plunged down obliquely into the top layer (Figure 1). The roots had been pruned 20 cm under the collar in the nursery. We also pruned them following a 20-cm diameter circle centred on the trunk. Structural roots were placed less than 7.5 cm deep not to affect tree development (Day et al., 2009), and the main axis of the roots was oriented N-S in each container. The trees were staked by a rigid structure placed at middle height (2 m) around the container. The experimental set-up consisted of 4 'soil' treatments (CO, SW, GW, SP) and 2 'plant' treatments (bare soil vs. tree-planted containers). We carried out measurements on the basis of destructive observations at three sampling times after the experiment was initiated: 1, 2, and 5 years on the bare soil containers, and 2.5, 4.5, and 5.5 years on the tree-planted containers (Table 2). Measurements on bare soil were conducted in the fall and measurements on the trees in the spring of the following year not to disturb fall tree growth. We installed 24 containers (4 soil treatments × 2 plant treatments × 3 replicates) on an experimental platform located in Angers from October 2004 to May 2010.

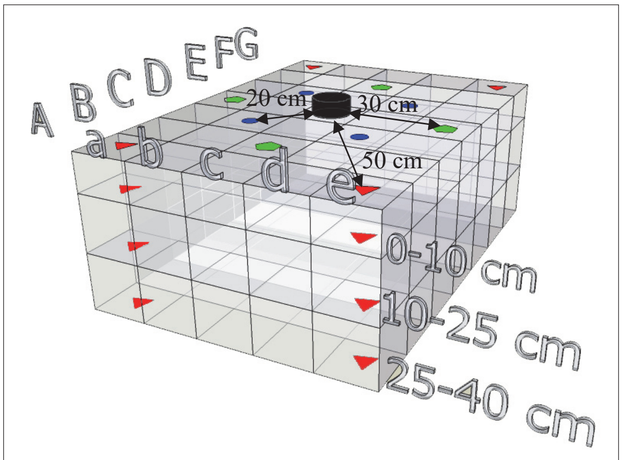


Figure 1. Diagram of the container volume divided into 105 blocks extracted from three depths. Triangles indicate the corner blocks (50 cm from the container centre), circles indicate four blocks next to the trunk (20 cm from the container centre), and pentagons indicate the blocks in-between the trunk and the edge of the container (30 cm from the container centre).

The climate was temperate, with 7.5 to 16.2°C mean annual temperatures, and 650 mm mean annual rainfall. Rainy spells were frequent but of low intensity. All the trees were drip-irrigated but not fertilized during the summer (from June to September, 1 L h^{-1} per drip, 4 drips per container, 2 hours a day, every three days).

Analyses

1. Tree measurements. Tree development can be assessed from organ formation, growth, and axes (a specialized term that describes branching). Organ formation, in other words organogenesis, is measured by counting the number of metamers. A metamer consists of an internode plus a node and one or several axillary buds and a leaf. Metamer length can be considered as a good marker of the growth rate and internal rhythm of plants (Galopin et al., 2011). We assessed vegetative growth by measuring trunk diameter 1 m from the ground, and from the length of metamers and axes. We characterized branching from the number and order of axes (axis orders are defined by successive branchings). Measurement frequency for each criterion is specified in Table 2.

We studied root development using the monolith method (Böhm, 1979). Each container volume was divided into 105 blocks (Figure 1). Thirty-five blocks were extracted from three depths: two depths in the organic matter layer (0–10 cm and 10–25 cm) and one in the soil layer (25–40 cm). For each different block, all the roots were hand-sorted, gently washed on a 2-mm sieve to separate roots from soil particles, and oven-dried to a constant weight at 40°C. Then for each block, total root biomass, > 5 mm diameter root biomass and < 5 mm diameter root biomass were measured. To evaluate the spread of the root system, we selected a few blocks according to their relative position to the trunk centre (Figure 1): 20 cm from the centre (near the trunk), 50 cm from the centre (at the four corners of the container) and 30 cm from the centre (halfway between the trunk and the corners). Then we measured root length density Lv (cm cm^{-3}), the length of roots per unit volume of soil, which is one of the main parameters required to understand plant performance, and we established three diameter classes: fine roots, < 1 mm; medium roots, 1–5 mm; coarse roots, > 5 mm. In the container with tree, we also measured weight and moisture in each block of each treatment to determine dry bulk density.

2. Soil measurements. We excavated three undisturbed cores (5 cm diameter, 6 cm height) from each 10-cm depth interval down to 50 cm. We determined soil water content values after oven-drying soil samples at 105°C for 48 h, and

Table 2. Measurements over time on trees and soils on the basis of non-destructive (trunk diameter, total number of axes, total axis order, near-saturated hydraulic conductivity) and destructive (total root mass, root length density, bulk density, structural stability) observations on bare soil and tree-planted soils.

		Bare soil						Tree-planted soils					
		Installation	1 year	2 years	2.5 years	4.5 years	5 years	Planting	1.5 years	2.5 years	3.5 years	4.5 years	5.5 years
	Sampling time	2004/10	2005/10	2006/10	2007/05	2009/05	2009/10	2004/10	2006/05	2007/05	2008/05	2009/05	2010/05
	Number of replications							*3*	*3*	*3*	*2*	*2*	*1*
Tree	Trunk diameter							x	x	x	x	x	x
	Total number of axes									x		x	x
	Total axis order									x		x	x
	Number of metamers											x	
	Length of metamers											x	
	Number of replications									*1*		*1*	
	Total root mass									x		x	
	Root length density									x		x	
	Number of replications	*1*	*1*	*1*			*1*			*1*		*1*	
Soil	Bulk density	x	x	x			x			x		x	
	Structural stability		x	x			x					x	
	Number of replications	*4*	*3*	*2*	*1*	*1*	*1*			*3*		*2*	
	Hydraulic conductivity	x	x	x	x	x	x			x		x	

calculated bulk density (g cm^{-3}) of the samples from the mass of the dry soil and the cylinder volume. In the tree-planted containers, we calculated soil bulk density in each block after root volume and root mass corrections. Root volume was determined by immersing roots in water to determine the volume of water moved by the immersed roots. To do this, dry roots (oven-dried at 40°C) were placed in a tea ball and then dipped into a basin filled with water and placed on precision scales. The same was done with the empty tea ball to determine its volume. We calculated dry root density ρ_{root} of *Ostrya carpinifolia* and found 0.76 g cm^{-3}.

Then soil bulk density ρ_{soil} in tree-planted containers was calculated using the following formula:

$$\rho_{soil} = \frac{M_{block} - M_{root}}{V_{block} - V_{root}} = \frac{M_{block} - M_{root}}{V_{block} - \frac{M_{root}}{\rho_{root}}} \qquad (1)$$

where ρ_{soil} is soil bulk density of the block (g cm^{-3}), M_{block} is the total mass of the block (g), M_{root} is the root mass of the block (g), V_{block} is the total volume of the block (cm^3), V_{root} is the root volume of the block (cm^3), and ρ_{root} is root density (g cm^{-3}).

For tree-planted (4.5 years) containers and bare soil (1, 2 and 5 years) containers, we measured structural stability as described by Le Bissonnais (1996). Samples from each layer of each set-up were sieved to collect 3- to 5-mm macro-aggregates. These aggregates were air-dried, maintained in a ventilated oven at 40°C for 48 h, and then analyzed. The analysis consisted of three series of tests aimed at assessing the resistance of aggregates to various breakdown mechanisms: fast and slow wetting tests to assess the resistance to slaking and micro-cracking, respectively, and mechanical breakdown test to characterize the resistance of pre-wetted aggregates (Le Bissonnais, 1996). The fast and slow wetting tests were performed on dried aggregates, and the mechanical breakdown test was performed on aggregates wetted with ethanol before immersion in water for the three tests. After the test, the wet samples were transferred to a nest of six sieves (2 mm, 1 mm, 0.5 mm, 0.2 mm, 0.1 mm, and 0.05 mm). For each test, we calculated the Mean Weight Diameter (MWD), i.e., the sum of the mass fraction recovered in each sieve multiplied by the average aperture between two adjacent sieves and expressed in mm. Each test was performed in triplicate.

Near-saturated hydraulic conductivity $K_{sat(-1cm)}$ was measured in the top undisturbed layer (0–10 cm) using a minidisk infiltrometer (Decagon Devices Inc., Pullman, WA, USA). Nine sub-samples were taken for each treatment. Measurements were carried out in a Mariotte chamber with a suction of 2 cm corresponding to an effective suction at a depth of -1 cm from the soil surface. On the basis of these infiltration measurements, hydraulic conductivity at near saturation $K_{sat(-1cm)}$ was calculated using the equation established by Zhang (1997):

$$K_{sat(-1cm)} = \frac{C_1}{A} \qquad (2)$$

where $K_{sat(-1cm)}$ is in m s^{-1}, A is a parameter that depends on soil, and C_1 is obtained from the calibration of the water infiltration measurement curve:

$$I = C_1 t + C_2 \sqrt{t} \qquad (3)$$

where I is the height of cumulative infiltrated water (m), t is time (s), and C_2 is a calibration parameter.

Statistical analyses

Up to 2.5 years from the beginning of the experiment, differences in trunk diameter, total number of axes and near-saturated hydraulic conductivity were determined by

TABLE 3. Morphological characteristics of the trees grown in control soil (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP) 4.5 years after planting ($n = 2$): total number of axis points, total number of 4-yr axes (2008 shoots), mean length of axes, total number of metamers per axis, and mean length of a metamer. Measurements were performed from base to tip. Means are compared per treatment; values with the same superscript letters are not significantly different (Tukey's test, $P < 0.05$).

	Total number of axes	2008 shoots			
		Total number of *n*-1 axes	Mean length of axes (mm)	Mean number of metamers per axis	Mean length of a metamer (mm)
CO	1260	534	29.1^{b}	3.96^{ab}	5.36^{c}
SW	3081	669	37.7^{a}	4.07^{a}	7.09^{b}
GW	1802	461	37.6^{a}	3.92^{b}	7.13^{b}
SP	1449	402	40.2^{a}	3.21^{c}	8.74^{a}

one-way analysis of variance using the statistical open source Software R (V.2.13.1). When the effects were found to be significant at $P < 0.05$, means were compared using Tukey's HSD test. When the number of containers was less than or equal to two for one treatment, we only presented the parameter mean or the value. For root length density, bulk density and structural stability, standard errors were calculated as an indicator of intra-container variability. Pearson's correlations or correlation coefficients (r) were also calculated using R.

Results

Tree measurements

We measured trunk growth over five growth seasons, from October 2004 (planting date) to May 2010 (following the 5th growth season) (Figure 2), and calculated relative diameter growth rates between 2 dates $((Dt_{n-1})-(Dt_n))/(t_n-t_{n-1}))$, where D = diameter in mm and t_n-t_{n-1} = a 1-year interval). Between May 2005 and May 2006, the relative diameter growth rate was low for CO and GW (0.24 and 0.36 mm $year^{-1}$, respectively) and high for SW and SP (0.56 and 0.52 mm $year^{-1}$, respectively). Between May 2006 and May 2007, CO, GW and SP exhibited similar relative diameter growth rates (around 0.40 mm $year^{-1}$), while SW had the highest one (0.66 mm $year^{-1}$). In May 2010, after five growth seasons, the tree grown in SW had the greatest diameter (73 mm, Figure 2), values for the trees grown in GW and SP were similar (66 and 64 mm, respectively) and the value for the tree grown in CO was the smallest (59 mm).

1. Characterization of axes. After 2.5 years, the total number of axes was statistically (Tukey's test, $P < 0.05$) higher for the SW tree (1,587 axes) than for the SP, GW and CO trees, with respectively 720, 654, and 613 axes (Figure 3). After 4.5 years, the ranking was the same, with the highest value for the SW tree (2,765 axes) as compared to the SP, GW and CO trees, with respectively 1,599, 1,239 and 1,174 axes. Maximum axis order was also observed for the SW treatment. It was 5 after 2.5 years and 8 after 4.5 years. After 4.5 years, we described the morphological characteristics of the axes produced the fourth year after planting (shoots of 2008, Table 3). The number of axes produced in 2008 was higher on the SW tree (669) than on the CO, GW and SP trees (534, 461, and 402, respectively). The mean length of axes was significantly lower on the CO tree (29.1 mm) than on the other trees (37.7, 37.6, and 40.2 mm for SW, GW and SP, respectively). The mean number of metamers per axis was significantly different among treatments (the highest on the SW tree, with 4.07 metamers per axis), and reflected meristem activity and organogenesis. The mean length of metamers reflected axis growth in length; the highest value was for the SP tree (8.74 mm), and the lowest for the CO tree (5.36 mm). We estimated total organogenesis in 2008 by calculating the total number of formed metamers from metamer number × mean

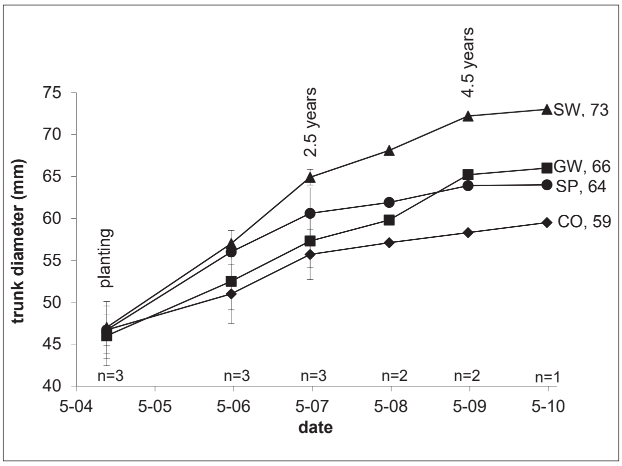


FIGURE 2. Evolution over 5.5 years of *Ostrya carpinifolia* trunk diameter 1 m above the soil line in the control (CO, ◆), soil + sludge/woodchip compost (SW, ▲), soil + green-waste compost (GW, ■), and soil + *sphagnum* peat (SP, ●) containers.

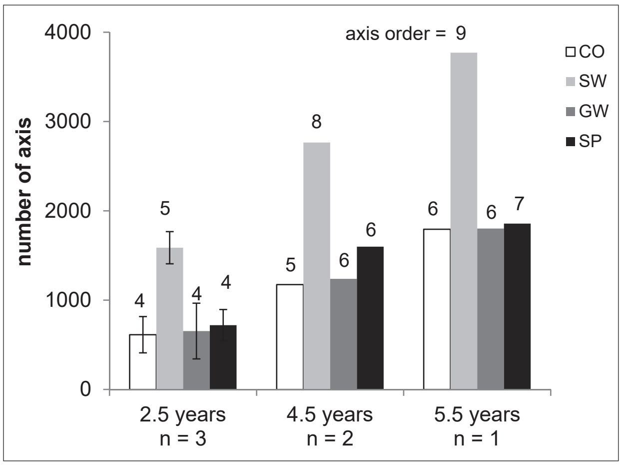


FIGURE 3. Number of axis points and axis orders as a function of the date after planting (2.5 years, 4.5 years, and 5.5 years) for the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP).

number of metamers (2,723 with SW, 2,115 with CO, 1,807 with GW, and 1,290 with SP), and total growth from metamer number × mean metamer length (19,306 mm with SW, 12,883 with GW, 11,336 with CO, and 11,275 with SP). SW yielded the highest organogenesis and growth values, SP the lowest organogenesis value, and CO and SP the lowest growth values.

2. Root characterization. Two years and a half and 4.5 years after planting, roots had mainly grown in the organic layer (0–10 and 10–25 cm) (Figure 4), and root mass in the deeper layer was very low and composed of < 5 mm diameter roots. After 2.5 years, total root dry mass was slightly

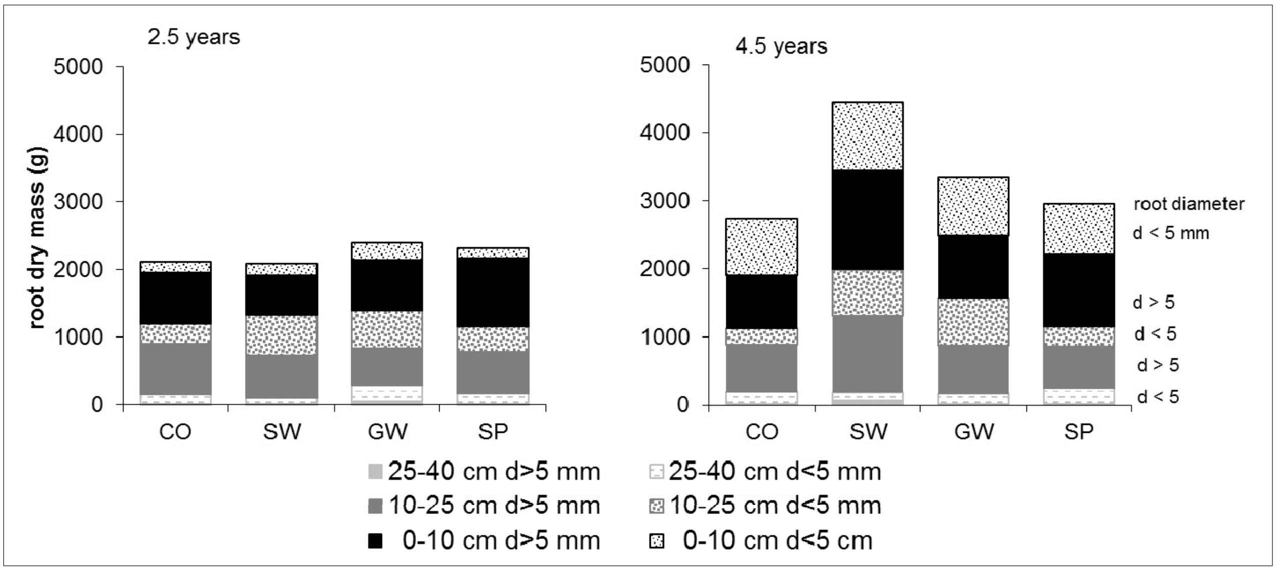


FIGURE 4. Large root dry mass (> 5 mm diameter) and fine and medium root dry mass (< 5 mm diameter) in the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost GW), and soil + *sphagnum* peat (SP) as a function of time after planting (2.5 years and 4.5 years) and depth in the container.

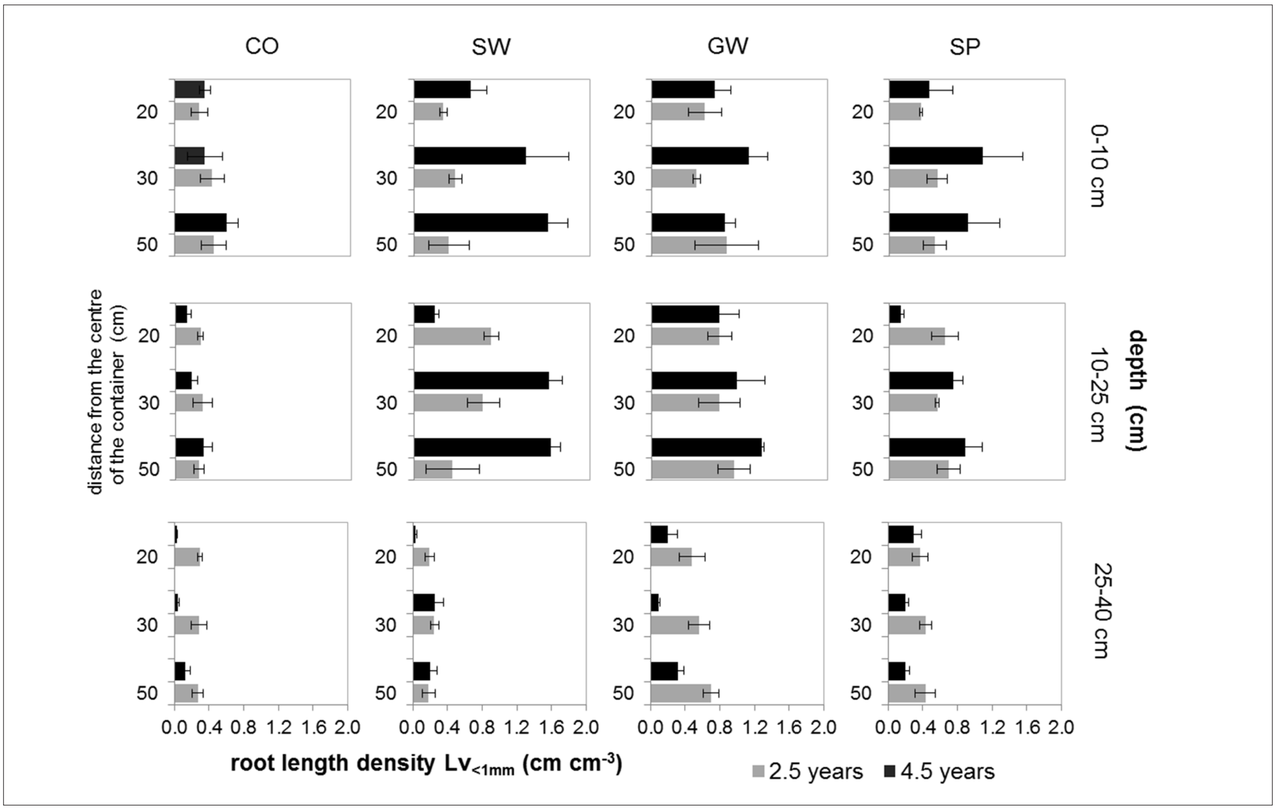


FIGURE 5. Root length density $Lv_{<1mm}$ of fine roots (< 1 mm diameter) according to their position relative to the trunk: 20 cm from the centre (near the trunk), 30 cm from the centre (halfway between the trunk and the corners), and 50 cm from the centre (at the four corners of the container) for the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP), as a function of time after planting (2.5 years and 4.5 years) and depth in the container. Bars represent the standard errors of four blocks in each container.

higher in the GW and SP trees, and lowest in the SW and CO trees. Fine and medium roots (<5 mm diameter) were mostly localized in the 10–25 cm layer. After 4.5 years, total root dry mass was the greatest in the SW tree, and the lowest in the CO tree. For all treatments, large roots (>5 mm) developed in the 0–10 cm layer, but a mass increase was only noted for the SW tree in this layer, and also in the 10–25 cm layer. Between the two dates, fine- and medium-root mass increased in the top layer (0–10 cm) for all treatments, and remained constant in the 10–25 cm layer. We calculated root length density Lv (cm cm^{-3}) on selected blocks (Figure 2) at the 3 depths, and also for each root class ($Lv_{<1mm}$, $Lv_{1\text{-}5mm}$, $Lv_{>5mm}$) at the two dates. For each root class, we studied root length density relative to the position from the center of the container, and we presented the evolution of $Lv_{<1mm}$ over time (Figure 5). After 2.5 years, fine roots had explored all the layers, and for a given treatment and a given depth, $Lv_{<1mm}$ values were very low for all depths. The organic layers (0–10 and 10–25 cm) had the highest Lv_{1mm} as compared to the bottom layer, and values were the lowest in CO for the 3 depths. As shown in Figure 4, GW and SP exhibited the highest values for fine root length density. After 4.5 years, fine root length density had increased in the organic layers (0–10 and 10–25 cm). Fine roots colonized the whole container, and $Lv_{<1mm}$ values were lower 20 cm from the centre occupied by the stump and the large roots. Fine root development was higher in SW at 30 and 50 cm from the centre than in GW and SP. In the bottom layer (25–40 cm), fine root density decreased over time.

Physical properties

1. Bulk density. Immediately after soil reconstitution, dry bulk density was considerably lower in the top layers of the organic mixtures (around 1.0 g cm^{-3}), than in the control soil (around 1.28 g cm^{-3}, Figure 6). In the underlying layer, dry bulk density was 1.29 g cm^{-3} for all treatments. After 4.5 years, at each depth, mean dry bulk density had considerably increased in the organic layer (0–10 and 10–25 cm) over time for all treatments, while height had remained constant for SW, GW and SP. After 1 year, organic matter had decreased bulk density in the bare soil containers for all treatments as compared to the control. But after 4 years, bulk density in the bare soil containers was considerably higher in GW than in SW and SP ($P<0.01$). After 5 years, these values had increased to 1.29 g cm^{-3} (0–10 cm) and 1.36 g cm^{-3} (10–25 cm) in GW, 1.12 and 1.13 g cm^{-3} in SW, 1.19 and 1.29 g cm^{-3} in SP, and 1.51 and 1.54 g cm^{-3} in CO. The values measured in the bare soil containers were comparable to those measured in the planted containers after 2.5 years and 4.5 years. After 2.5 years, in the 0–10 cm and 10–25 cm layers, roots had decreased bulk density in GW and CO, and maintained the same value in SW and SP. After 4.5 years, roots had decreased bulk density in CO and SP, but had maintained it in SW and GW. In the underlying layer of soil material alone (25–40 cm), layer height decreased from 28 cm to 19 cm throughout the 5 years for all treatments. In that layer, bulk density values were higher in the planted containers than in the bare soil ones.

2. Structural stability. We compared structural stability at different depths for the more destructive test (rapid wetting test or slaking test) (Figure 7) in the bare soil and planted containers (4 years and 4.5 years, respectively) to assess the effects of root development on aggregate resistance. In the organic layer (0–10 and 10–25 cm), the rapid wetting test was very destructive in the bare soil containers, and mean weight diameter (MWD) was lower than 0.5 mm, revealing a breakdown of aggregates to smaller sizes except for SW. Bare

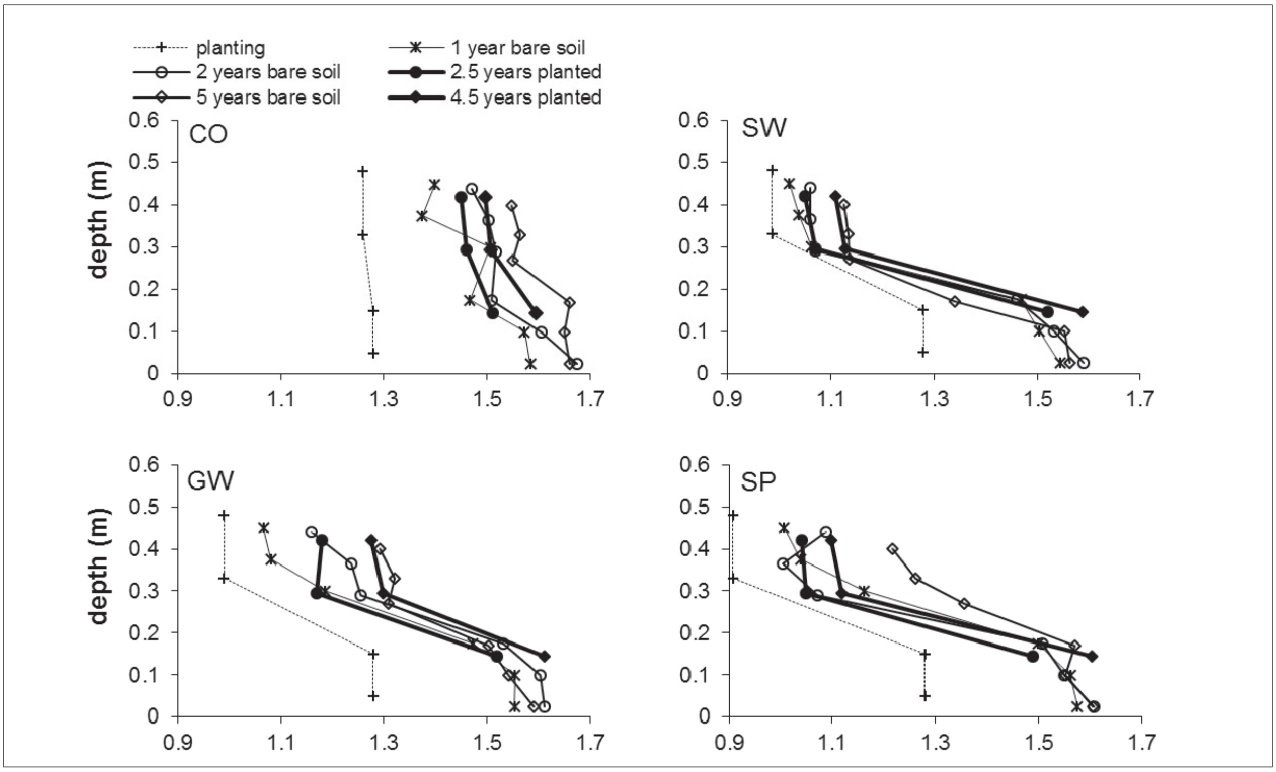
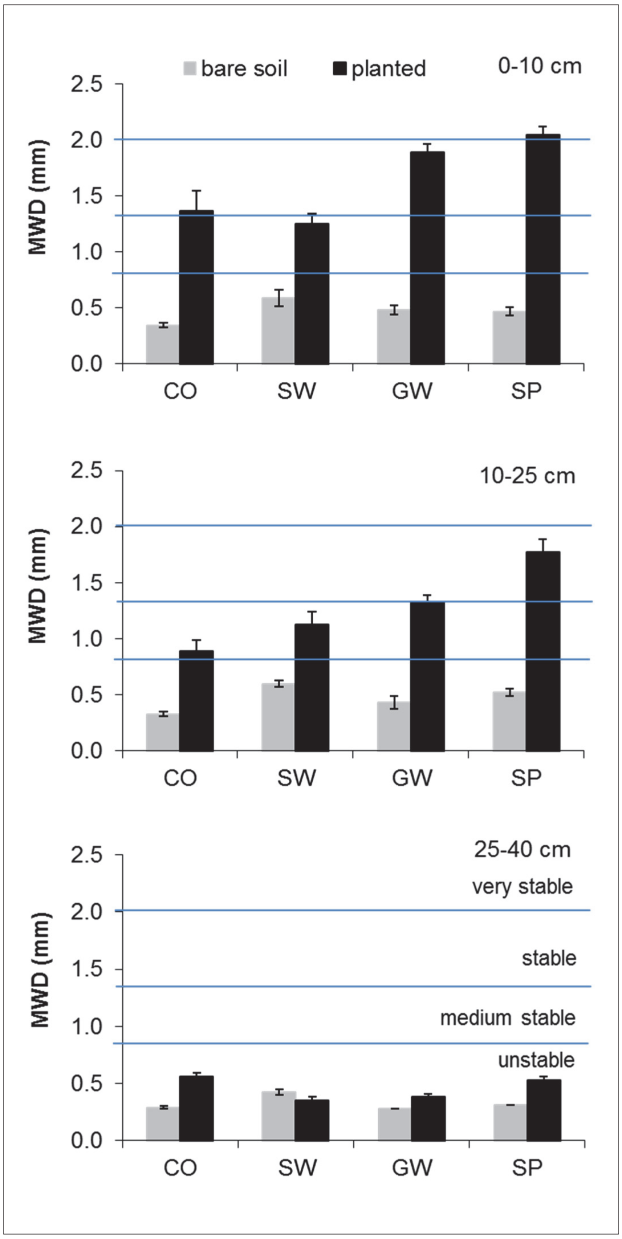


FIGURE 6. Dry bulk density in planted and bare soil containers for the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP) as a function of time after installation (1 year, 2 years and 5 years), or after planting (2.5 years and 4.5 years) and depth in the container. The bottom of the container corresponds to level 0.



soil aggregates were unstable and poorly resistant to slaking, but in the planted containers resistance to slaking significantly increased. In the 0–10 cm layer, this improvement was considerable in GW and SP, with MWDs equal to 1.8 and 2.1 mm, respectively, and aggregates were stable (GW) or very stable (SP). In CO and SW, aggregates were relatively stable. In the 10–25 cm layer, SP exhibited stable aggregates, and SW, GW and CO exhibited relatively stable ones. In the underlying layer (25–40 cm), aggregates were unstable in all treatments, whether planted or not, without any difference among them.

3. Hydraulic conductivity. After 2 years in the bare soil containers and 2.5 years in the planted containers, there was no significant difference ($P < 0.05$) in saturated hydraulic conductivity in the top layer (0–10 cm) in the soils mixed with organic products, except for CO (Figure 8). After 4 years in the bare soil containers and 4.5 years in the planted containers, organic matter had increased Ks 4.5-fold in SW, 5-fold in GW, and 2.3-fold in SP as compared to CO. In the planted containers, roots increased saturated hydraulic conductivity as compared to the bare soil container.

Discussion

Effects of organic matter

In accordance with the literature (Aggelides and Londra, 2000; Rawls et al., 2003; Vidal-Beaudet et al., 2009), high organic matter inputs (50 g C kg^{-1} dry matter) improved physical properties [dry bulk density (Figure 6), saturated hydraulic conductivity (Figure 8)] in the mixtures as compared to the control. On the same experimental site, in the bare soil containers over the first 24 months, organic matter increased structural stability and modified aggregate organization. Pore distribution became bimodal in the mixtures,

Figure 7. Structural stability after 4.5 years expressed as MWD for the rapid wetting test for control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP) in planted and bare soil containers. Bars represent the standard errors of three replications in each layer of each treatment.

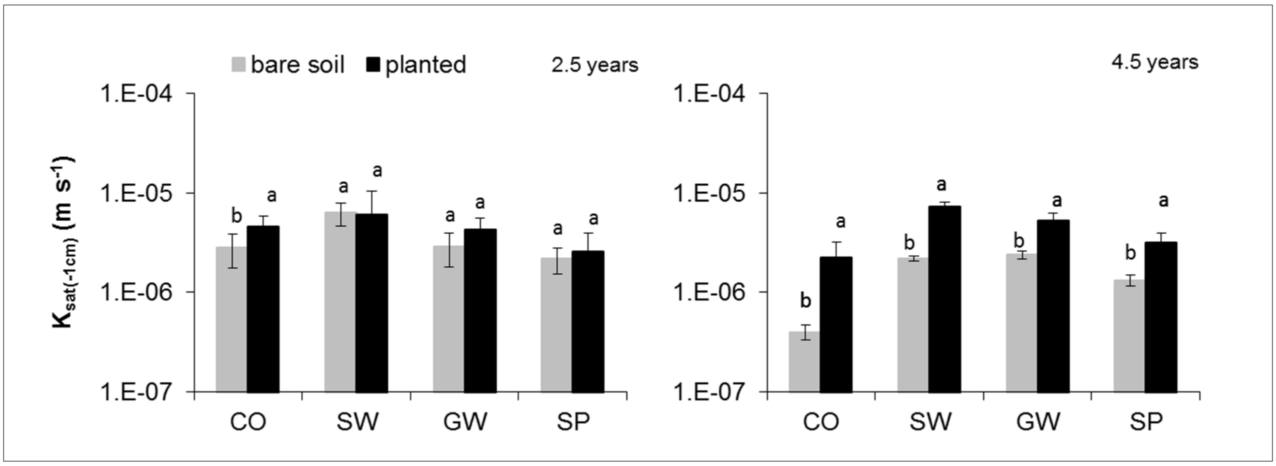


Figure 8. Comparison of hydraulic conductivity values after 2.5 years and 4.5 years measured with a disc infiltrometer in the organic layer (0–10 cm) of the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP) in planted and bare soil containers. Bars represent the standard errors of nine replications or subsamples of each treatment. Different letters indicate significant differences between planted and bare soil treatments at $P < 0.05$ for a same date (Tukey's HSD test).

and new porosity appeared, with elongated pores (>550 µm radius) (Grosbellet et al., 2011). Soil water retention was also improved after 5 years (Cannavo et al., 2014). High organic matter inputs improved vegetative growth above and belowground, as described by Smith et al. (2010). Shoot growth depends on species, but also on growing site physical properties (Riikonen et al., 2011). As early as after 2.5 years, SW had had a significant effect ($P<0.05$) on aboveground growth dynamics (total number of axes and axis number), and this effect was maintained after 4.5 years with two trees per treatment. Organic matter increased the length of the axes developed in the fourth year as compared to CO: +0.29 mm mm^{-1} for SW and GW, and + 0.38 mm mm^{-1} for SP (Table 3). As adult shoot and tree root measurements are highly time-consuming, we did not replicate each treatment after 2.5 years, so we admit a risk related to the absence of replication for root growth comparison among treatments. But we used clones to reduce the large growth variability in order to delineate a trend in treatment effect for $n=2$ and $n=1$. Organic matter increased belowground growth (root mass and root length density), but the roots were mainly located in the organic layer and did not colonize the control underlying layer. This behavior corresponds to that of temperate trees that have 26% of their root mass in the upper 0.1 m (Gregory, 2006), and 45% in the top 30 cm of soil for *Quercus* and *Platanus* (Gilman, 1996). Root length density is relevant to express the soil-root contact surface. As for aerial development, SW yielded better $Lv_{<1mm}$ results after 4.5 years than other organic matters and CO (Figure 5, 0–10 and 10–25 cm). The difference between the two composts could be linked to organic matter maturity. During the experimentation, we showed that GW was unstable as compared to SW and not as mature as expected, and decomposition of its organic matter took more than 2 years after application (Vidal-Beaudet et al., 2012). In this situation, the stability of GW organic components impacted oxygen consumption for substrate degradation (Balakina et al., 2005) and reduced available oxygen for the roots.

Architectural development

We analyzed the components of the growth and development of trees after planting based on crown architectures and root systems. We assessed organogenesis from the number of metamers. As regards growth in 2008, organogenesis was twice as high in SW as in SP, with respectively 2,723, 2,115, 1,807 and 1,290 metamers for SW, CO, GW and SP. The high number of axis order of the trees grown in SW and GW showed that organogenesis was linked to terminal meristem activity and also to axillary meristems that induced axillary axis growth. Organogenesis of axillary buds induced great numbers of axes; it was twice as high in SW as in SP, with respectively 3,081, 1,802, 1,449 and 1,260 total axes for trees grown in SW, GW, SP and CO. This degree of branching was confirmed by the order of ramification (Figure 3), which contributes to the development of the tree and the restructuring of the crown according to its architectural model. We assessed growth in 2008 by measuring metamer length and total axis length. SW induced high growth but the other three treatments did not, with respectively 19,306, 12,883, 11,336 and 11,275 mm for SW, GW, CO and SP. After transplanting, the trees developed roots for water and nutrient uptake. The low number of anchorage and exploration roots, subsequent to nursery pruning and transplanting, did not guarantee restoration of *Ostrya carpinifolia* root architecture and maintained the trees in a vulnerable situation. The SW mixture was the only one that ensured durable recovery of the tree after transplanting, with significant growth and development. Root architecture displayed a higher number of roots in SW and a superficial location in the top 25 cm of soil.

We linked belowground and aboveground growth to determine correlations between our main parameters (Table 4). Although we did not have 3 replicates per treatment, conclusions can be drawn from these measurements. After 2.5 years, we observed a good correlation only between trunk diameter and the number of axes (0.910). Root parameters were not linked to aerial parameters, but <5 mm diameter root mass was well linked to mean $Lv_{<1mm}$ in the 0–25 cm layer (0.847). After 4.5 years, we observed a good correlation between trunk diameter and the number of axes (0.886), total root dry mass (0.952), <5 mm diameter root mass (0.838), and $Lv_{<1mm}$ (0.956) in the organic 0–25 cm layer. Total root dry mass was also highly correlated with the number of axes (0.910). Mean $Lv_{<1mm}$ was highly correlated with total root dry mass (0.889) and <5 mm diameter root mass. These results confirm that trunk diameter can be a good, easily measurable indicator of architectural development below and aboveground after planting (Day et al., 2010). Trunk diameter growth throughout the experiment (Figure 2) was linked to soil physical and chemical properties and consequently to the degradation of the organic matter and to the release of the nutritive elements resulting from this

Table 4. Correlation coefficients (r) between aboveground tree components (trunk diameter, total number of axis points) and belowground tree components (total root dry mass, total root mass (<5 mm), mean $Lv_{<1mm}$ 0–25 cm), 2.5 years and 4.5 years after planting. Values in bold are significant correlations at the 0.05 probability level.

Time after planting		Trunk diameter	Number of axes	Total root dry mass	Root mass (<5 mm)	Mean $Lv_{<1mm}$ 0–25 cm
2.5 years	Trunk diameter	1.000				
	Number of axes	**0.910**	1.000			
	Total root dry mass	-0.341	-0.590	1.000		
	Root mass (<5 mm)	0.131	0.178	0.505	1.000	
	Mean $Lv_{<1mm}$ 0–25 cm	0.381	0.206	0.662	0.847	1.000
4.5 years	Trunk diameter	1.000				
	Number of axes	**0.886**	1.000			
	Total root dry mass	**0.952**	**0.910**	1.000		
	Root mass (<5 mm)	0.838	0.592	**0.870**	1.000	
	Mean $Lv_{<1mm}$ 0–25 cm	**0.956**	0.715	**0.889**	**0.926**	1.000

degradation. Vidal-Beaudet et al. (2012) showed during this experiment that the degradation intensity of the organic matter was related to the nature of this matter. The decrease in total organic C in the mixtures was observed mainly in the coarse fractions during the first year and was due to degradation mechanisms linked to biological activity. SP and SW induced high trunk development in the first eighteen months, indicating a high degree of restoration of the water and mineral absorption properties of the root system probably related to the physical properties of peat and sewage sludge compost. After 2.5 years, the slow growth observed in SP over the following months is easily explained by the low initial nutritional level in P_2O_5 and K_2O of peat (Figure 9) and the decline in biological activity over time (Wiseman et al., 2012). Vidal-Beaudet et al. (2012) showed that the peat organic matter is stable with a low mineralization potential and it is in agreement with the availability of nutrients over time. These results are in accordance with those obtained by Niklasch and Joergensen (2001). The mineralization potential values determined in controlled conditions indicated that SW was a moderately stable compost (Vidal-Beaudet et al., 2012). For GW, the high mineralization potential values confirmed that this compost was unstable and not as mature as expected. Several studies showed that compost mineralization slows down as its maturity degree increases (Bernal et al., 1998) and this phenomenon reduces the release of nutrients. In waste constructed Technosols, Vidal-Beaudet et al. (2018) showed that the nutrient availability and the transfer of P to plant were highly dependent on organic matter type, with high or low delivery of P_{Olsen} linked to the mineralisation potential.

SW consistently maintained trunk development throughout the experimentation, and also good recovery of the root system in relation to a good initial nutritional level in P_2O_5 and K_2O, whose values were above the admitted satisfactory nutrient level. In GW, the initial level of P_2O_5 was lower than in SW and below the critical level, but high organic matter mineralization potential still provided adequate amounts of available P and K five years after planting (Figure 9). The CO treatment was penalized by its low physical properties and low initial nutrients contents. We observed a significant correlation between $Lv_{<1mm}$ and P_2O_5 (0.911) and K_2O (0.941).

Two phases were distinguishable during the 4.5 years following the transplanting stress. During the first phase, absorption was restored via the root hair system, allowing the tree to perform its vital functions, with possible remobilization of its internal reserves. During that phase, soil physical properties and climatic conditions were essential. The second phase, under good growth conditions, was the restructuring of the aerial and belowground architectural model. It was measured by the increase in trunk diameter and crown differentiation axes (Atger and Edelin, 1994).

Roots and soil physical properties

Organic matter content and bulk density influence root length density. But how tree roots can in turn modify soil structure is yet another question. In agricultural soils, the effects of plants on soil structure cannot be distinguished from the management practises associated with cultivation (Angers and Caron, 1998). We added organic matter from the start in one go and then, several years after planting, we distinguished the effects of roots on soil structure changes. In the organic layer, height remained constant throughout the 5 years. Despite an organic matter content >25% (v/v), we did not record any anaerobic problem linked to organic matter mineralization, as stated by Craul (1994). Root density decreased in the underlying layer in all treatments. A dry bulk density of 1.6 g cm^{-3} can decrease fine root growth (Cubera et al., 2009). In our experiment, bulk density values remained below 1.6 g cm^{-3} in the top layer (0–10 and 0–25 cm) for all treatments over time. At 40-cm depth, bulk density was higher than 1.64 g cm^{-3} and physically limited fine root growth. Bruand et al. (1996) showed that the fine soil surrounding the root has a high bulk density of 1.8 g cm^{-3}, and root growth can locally compact the soil and alter microporosity. But in homogeneous soils, density decreases exponentially with the distance from the root-soil interface (Gregory and Hinsinger, 1999). Roots have a great capacity to reinforce soils and improve mechanical stability (Mickovski et al., 2009). We showed that roots decreased dry bulk density in the layers of the GW and SP containers, and found a good correlation between $Lv_{<1mm}$ and dry bulk density measurements (0.73).

In the underlying layer (25–40 cm), height had strongly decreased after 24 months (by 7 to 8 cm, from 28 cm initial

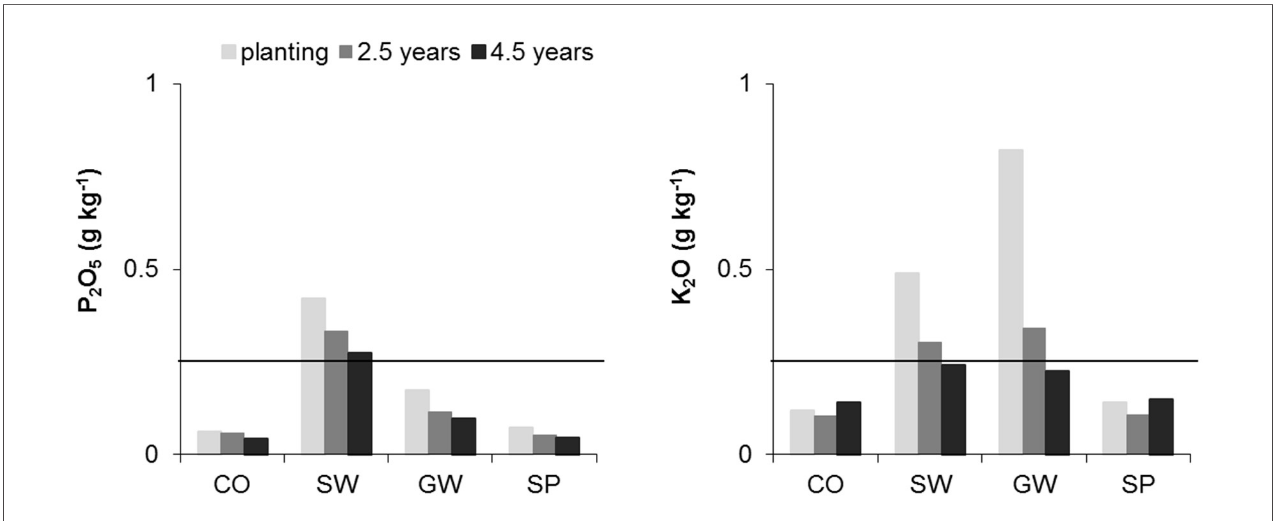


FIGURE 9. Contents in available P_2O_5 and K_2O (g kg^{-1}) over time in planted containers in the top layer (0–25 cm) of the control (CO), soil + sludge/woodchip compost (SW), soil + green-waste compost (GW), and soil + *sphagnum* peat (SP). The line corresponds to satisfactory nutrient levels for tree growth.

height) and dry bulk density was close to the root growth threshold value in sandy loam soils: 1.6 g cm^{-3} (Zisa et al., 1980; Jim, 1998). The planted container had higher dry bulk density values (1.68 g cm^{-3}) than the bare soil one. We can hypothesize that dry bulk density increased due to layer settlement caused by the tree weight. Dry bulk density higher than the threshold value increased mechanical resistance to root growth in the deeper soil. That is why total root dry mass and root length density were very low in that layer. Root-soil contact depends on dry bulk density but also on the aggregation level. A good contact can help water and nutrient uptake and plant development. By taking up water, roots induce drying-wetting cycles that modify soil structure (Van Noordwijk et al., 1993). Roots at the root-soil interface increase clay aggregation on fine silt micro-aggregates (2–20 µm) and improve structural stability through organo-mineral association around the roots (Watteau et al., 2006). Root-soil contact is best in soils with small-size aggregates (< 0.5 mm) (Schmidt et al., 2012). In our study, roots had a significant effect on stable macro-aggregate (> 3.15 mm) formation in all treatments, independently of the macrofauna and especially of earthworms that were in very low numbers. The increase in aggregate stability in the top layer (0–10 cm), due to the presence of roots in planted treatments as compared to the bare soil treatment, was approximately 2-fold in SW, 3.9-fold in GW and CO, and 4.4-fold in SP. In the 10–25 cm layer, the enhancement factor was 1.9 in SW, 2.7 in CO, 3.0 in GW, and 3.4 in SP. Organic matter nature also plays a role in the development of supportive agents for macro-aggregation such as fungal hyphae (Tisdall and Oades, 1982) and polysaccharides (Angers and Caron, 1998). We observed the presence of ectomycorrhizal hyphae in SP, which was the treatment with the highest MWD (2.05 mm in the 0–10 cm layer, and 1.77 mm in the 10–25 cm layer). Better aggregate stability is expected to lead to a modification of the structure of the mixtures, with new organization of the aggregates and an evolution of pore size distribution, with macropore formation beneficial to water flow. The number of macropores in the rhizosphere and infiltration increase under high matrix potentials (Whalley et al., 2004). Water flows preferentially along tree roots, and this induces macropore flow in the topsoil (Bogner et al., 2010). Tree roots can increase the infiltration rate through a structural soil mix 27-fold as compared to a bare soil container (Bartens et al., 2008). For Bramley et al. (2003), infiltration was 2 to 17 times faster in tree-planted containers than in bare soil containers. To highlight the evolution of porosity induced by roots, we compared saturated hydraulic conductivity in the top 10 cm of the planted and bare soil containers after 4.5 years. In the bare soil containers, Ks in the control was 4×10^{-7} m s^{-1}, i.e., slow permeability, and the organic layers displayed moderately slow permeability (FAO, 2001). In the planted containers, roots significantly increased saturated hydraulic conductivity with a highly significant correlation (0.98), by 1.2-fold in the control, GW and SP, and 2.3-fold in SW. But conductivity values remained moderately low for all treatments. Therefore, all treatments were under the critical soil conductivity level recommended to landscape managers – $Ks = 1.55 \times 10^{-5}$ m s^{-1} (Craul, 1999) – that distinguishes between the most favourable and the least favourable growth conditions for roots. Possible reasons for this low increase may be that (i) the trees were still young, and the roots reduced conductivity because root growth blocked channels available for water flow after root degradation (Meek et al., 1992), or (ii) the volume of soil available for root development was already too small and root growth opportunity was reduced.

Conclusion

Five years after planting, the composts had improved root and shoot development but peat had not. The composts increased trunk diameter, the total number of axes, axis length, and favoured organogenesis (number of metamers, axis order). High levels of compost also induced considerable total and fine root development (total root mass, root length density). The roots were mainly located in the organic layer and did not colonize the underlying layer. Correlation coefficients between aboveground and belowground tree components confirmed trunk diameter as a very good indicator of tree above and belowground architecture. The effect of organic matter on tree development was linked to its type and maturity. The green waste compost was not as mature as expected, so it was not as efficient as the compost made from sewage sludge and wood chips. *Sphagnum* peat was the least efficient organic product and did not seem sufficient to lead to a long-term improvement of root growth as compared to the control. Compost mineralization provided sufficient amounts of available P and K in the compost mixtures over 5 years.

The addition of high levels of organic composts and peat to the soil immediately improved its physical properties, e.g., dry bulk density, and in return fine tree roots modified soil structure and decreased dry bulk density in the top layer. The roots had apparent effects on stable macro-aggregate formation and structural stability. Root development had also significantly improved hydraulic conductivity after 4.5 years.

In this same experiment, Cannavo et al. (2014) predicted that high organic matter amendment could maintain physical properties ten years after soil reconstitution in bare soil containers. We have demonstrated here that the choice of the type of organic matter (high fertility with co-compost of sewage sludge and wood chips, medium fertility with green waste compost and low fertility with peat), used for constructed soil design, plays a determining role in the early establishment of street trees and therefore determine their longevity. In return, fine root development favoured by organic matter appears to have a beneficial effect on soil structure and the long-term maintenance of the high performance of its physical parameters (bulk density, aggregate stability, hydraulic conductivity).

The mixtures designed for tree planting hole with high exogenous organic matter input and tested during this experiment are efficient to develop fertile soils, providing the suitable soil functions for a sustainable urban landscape management: support of plant growth, reduction of threats on natural resources as peat by using composts, and water filtering. These results could help green space managers to get sufficient technical and scientific knowledge to construct fertile and sustainable urban soil for urban planting. To develop urban horticulture, it is essential to educate all the city makers (landscape architects, civil engineers, urban planners, municipal officials and urban farmers) about optimal soil specifications expected for fertile urban soils: choice of organic matter nature, sources of organic matter or mineral material, proportions of organic matter in term of soil structuring, soil profile design. Further studies are necessary to (i) identify and report sustainable materials that may be suitable for soil construction, and (ii) propose constructed soil design profiles linked with land-uses.

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