

Use of coarse substrate to increase the rate of water infiltration and the bearing capacity in tree plantings

Francesca Bretzel^{a,*}, Francesca Vannucchi^a, Roberto Pini^a, Manuele Scatena^a,
Alessandro Marradi^b, Fabrizio Cinelli^c

^a Research Institute on Terrestrial Ecosystems (IRET), CNR, Via Moruzzi 1, 56124 Pisa, Italy

^b Department of Civil and Industrial Engineering (DiCI), University of Pisa, Italy

^c Department of Engineering of Energy, Systems, Territory and Construction (DESTeC), University of Pisa, Italy



ARTICLE INFO

Keywords:

Engineered soil
Chlorophyll content index
Shoot growth
Small leaved linden
Soil compaction
Urban roadsides

ABSTRACT

This work assesses the suitability of recycled crushed bricks and compost, used as a mixed growing substrate, in urban roadside plantings of *Tilia cordata* Mill. Coarse recycled materials can prevent compaction, improving air and water flows in the rhizosphere, and thus reducing tree mortality or poor growth. In addition, compost is a source of organic matter, contributing to enhance soil quality. Six substrates were tested: 1) soil; 2) crushed bricks 0–30 mm; 3) crushed bricks 6–30 mm; 4) soil + compost (15% v/v); 5) crushed bricks 0–30 mm + compost; and 6) crushed bricks 6–30 mm + compost. Trees were planted in $0.6 \times 0.6 \times 0.6$ m pits, filled with the six different substrates. The water infiltration rate (K_f) and load bearing capacity (E_{vd}) of the substrate were monitored along with the shoot length, and chlorophyll content of the trees. At the end of the trial, the root biomass and total root length were measured. Crushed bricks positively affected K_f and E_{vd} ; the presence of compost decreased the value of bearing capacity. 0–30 crushed brick substrates (with or without compost) increased the linden shoot length and enabled to develop higher root biomass, compared to the soil (+72%) and 6–30 (+37%). The best trade-off between resistance, compaction and plant growth was 0–30 mm crushed bricks. This research provides evidence that a coarse matrix substrate made of crushed bricks is efficient in preventing compaction and allows plant growth.

1. Introduction

Urban roadside soils can be highly compact with altered C and N cycles, which limit tree growth and stability (Jim and Ng, 2018; Lorenz and Lal, 2009). In addition, the scarcity of organic matter, due to the mix up of the surface and deeper soil (Craul, 1992; Jim, 2001) reduces the pedofauna activity and aggravates the compaction caused by surface loading (Mullins, 1991). The infiltration rate dramatically decreases in compacted soils, thus reducing the water supply and increasing the risk of waterlogged conditions (Gregory et al., 2006). Trees planted in urban roadsides are subject to underground constraints such as poor drainage and root anoxia, as well as a lack of soil structure and organic matter, leading to tree planting failures (Jim, 2001). However, wide unpaved areas of soil around the tree pits facilitate the healthy development of plant canopies (Day and Amateis, 2011). The incorporation of organic matter or mature compost also reduces soil bulk density values, and thus compaction (McGrath and Henry, 2016). In addition, trees used in urban landscaping need to be highly

morphologically and physiologically flexible in order to adapt to the difficult conditions and survive (Passioura, 2002). In some cases, maintenance programs should be planned in the initial years after planting (Koeser et al., 2014) and an appropriate selection of tree species helps to reduce the consequences of high compaction (Ow and Ghosh, 2017), but cannot eliminate them.

Various substrates that resist compaction have been proposed as rooting media for urban trees, which are referred to as engineered, structural or skeletal soils. They are made up of different materials whose grain size distribution, organic matter content, water holding capacity and drainage are studied to meet the needs of young trees. The coarse materials are mainly stones or gravel or expanded slate that act as load bearers; they vary in size from 12 to 38 to 25–35 to 60–150 mm; the relation soil to stones varies from 1:3–1:5 (Grabosky and Bassuk, 1995; Bartens et al., 2010; Bühler et al., 2017).

Below we report some of the studies on the incorporation of coarse matrix soil to enhance the load-bearing capacity. Bartens et al. (2010) studied *engineered* soils that improve root development and tree

* Corresponding author.

E-mail address: francesca.bretzel@cnr.it (F. Bretzel).

stability in urban plantings, but in species-specific ways, without all species benefitting from them. Ow and Ghosh (2017) found that in structural soils, the infiltration rate affects tree growth, and that the roots are encouraged to develop in load-bearing layers in a continuous coarse matrix, established with a small number of fine particles distributed in the relatively large pores between the coarse fragments (Bühler et al., 2017).

The prevention of soil compaction before planting is usually preferred over expensive post-planting treatments which are difficult to apply, insufficiently effective and may injure plant roots (Kozłowski, 1999). Rebuilding the soil profile by incorporating organic matter at depth on established tree plantings can enhance plant growth (Layman et al., 2016).

Crushed bricks, compost, sludge, coconut shells, and sawdust are some of the recycled materials tested to create the substrate used for urban green infrastructures (Koolen and Rossignol, 1998). However, in order to reduce the costs and impact of transport, the materials employed should be available locally. Crushed bricks can store nutrient elements and water, which contribute to plant development (Nehls et al., 2013). Compost from municipal waste is produced in huge amounts and represents a valid source of organic matter for urban plantings. Crushed bricks and compost are commonly available in urban areas and are both low cost materials.

The linden is a common ornamental tree for urban plantings (Day and Amateis, 2011), especially on urban roadsides, and the species *Tilia cordata* Mill. (small-leaved linden) has small leaves, which are more manageable for urban street cleaning. It also does not produce suckers and is suitable for planting in paved cut-outs (Rahman et al., 2019). However, the lack of urban soil permeability negatively affects the healthy linden growth, i.e. shoot growth and stem lengths (Sand et al., 2018).

The aim of this study was to assess the suitability of mixed crushed brick and compost substrates to provide compaction-resistant and well-drained tree rooting volumes. In a three-year experiment, we thus evaluated the growth performance of linden trees (*Tilia cordata* Mill.). The substrates were composed of recycling building materials found at a local company. A compost from municipal waste was also employed to evaluate the influence of organic matter on the different substrate parameters and on the plant growth.

2. Materials and methods

2.1. Experimental design

The experiment was carried out at the Anchione nursery of Euroambiente (Zelari Group, Pistoia, Italy), where the annual rainfall and min/max average annual temperature in the three experiment years were respectively: 761 mm 8.7°/23.1 °C; 1000 mm 8.9°/22.4 °C; 1447 mm, 9.1°/21.5 °C. The experiment was carried out in a completely randomized design with six replications (Fig. 1). Six substrates were tested 1) soil (control); 2) 0–30 mm crushed bricks; 3) 6–30 mm crushed bricks; 4) soil + compost; 5) 0–30 mm crushed bricks + compost; and 6) 6–30 mm crushed bricks + compost. The trials were all carried out using local soil. Compost was incorporated into the substrates at 15% v/v prior to filling the pit, and hand mixed with a shovel (C = compost treatment; NC = no compost treatment). From the range available, we adopted the crushed brick range of particles most suitable for growing trees (Grabosky and Bassuk, 1995). We chose a local supplier in order to increase the value of the material found on site.

The trees in our study were 4–5-year-old seedlings, 2.5 m tall, with a trunk diameter of 5–10 cm, and balled and burlapped (about 30 cm diameter). The tree pits (60 × 60 × 60 cm = 216 l) were dug twice the volume of the root ball and in the same soil used for the control. They were arranged in two lines, with a distance of 3 m between the lines and the distance from one pit to another along the line was 2.5 m.

In the spring of the first year, in February 2011, each pit was filled

with the substrate for 30 cm, then the plant was placed at the center and covered with the rest of the substrate, so that the collar was at the soil surface. During each summer, plants were irrigated periodically: 4 l/plant, three times a week in May and June, and every day in July and August, due to the greater drought of the latter period. No pruning and fertilizations were carried out.

2.2. Substrate analysis

Prior to the experiment, 0–30 and 6–30 material textures were analyzed (Gee and Bauder, 1986). The grain size distribution of the crushed bricks was compliant with UNI EN 933-1 (1999). The results are reported in Fig. 2. The two materials were different in the percentage of particles characterized by the size < 1 mm (22.2% in 0–30 and 1.3% in 6–30). The soil had a sandy loam texture (51% sand, 30.5% silt, 18.5% clay).

Each component of the substrate, soil, crushed bricks and compost, was characterized using standard methods (ASA-SSSA, 1996) in terms of pH (H₂O); total nitrogen (N_{tot}) and organic carbon (C_{org}) (dry combustion using RC-412 MULTIPHASE CARBON Leco); and available phosphorous (P) (Olsen Method). The chemical properties of the original materials employed for the substrates (soil, bricks and compost) are reported in Table 1. The compost originated from municipal source-separated solid waste, which was provided by SienAmbiente. Compost incorporation into the substrates increased the N_{tot} and C_{org} content to 0.25% and 3.6%, respectively.

Twice a year, the soil was compacted by running a Range Rover (1000 Kg) over the ground beside the holes. The bearing capacity was measured as a dynamic module (E_{vd}), on each pit using a falling weight deflectometer “Terratest 3000”. The E_{vd} was calculated using the average of the deflection peaks, recorded in the three measurement falls, performed on each pit, in July, after the Range Rover had driven over it. The water infiltration rate (K_f) was measured using a prallplate with a diameter of 15 cm, laid on each substrate, and pouring 2 l of water from a height of 10 cm for 5 s (Pregl, 1999). The infiltration time was measured in seconds. The infiltration rate, K_f (m/s) was calculated as follows:

$$K_f = 10^{k \cdot \log \log (x+d)}$$

where $k = -21,307,725$ and $d = -18,141,758$ (Pregl, 1999).

2.3. Tree growth and chlorophyll content monitoring

In July each year until the end of the experiment, the growth form and vigor of trees, expressed as the main length of the shoots of each plant, were monitored without the use of destructive methods (Archibald and Bond, 2003). Trunk circumferences were recorded at 1.3 m (breast height) with a tape measure, each year at the end of the growing season. Weighted values were calculated by dividing the difference in trunk circumference between the first and second years by the value of the first year trunk circumference. The lengths of the shoots were recorded using a carpenter's ruler on the same three branches on each plant, randomly selected in full sun exposure. At the same time, the leaf chlorophyll index was measured, at midday, by a SPAD-502 chlorophyll meter (Minolta Camera Co., Ltd., Japan) in full sun, completely expanded IV and V leaves, located on the previously selected branches. The leaves were healthy and damage free and the measurements were taken at the mid-point of leaves avoiding the mid-rib (Muñoz-Huerta et al., 2013).

The experiment ended after three years. The plants were dug out from the pit at a depth of 60 cm. An Air-Spade® 2000 Arbor/Landscape Kit was used which enables the roots to be dug out with a diameter of > 1–3 mm, thus obtaining the mass of roots in the pitfall. We separated the root system, obtained by cutting the roots at the collar level with a saw, into the main roots and dried them in an oven (ISCO 9000)

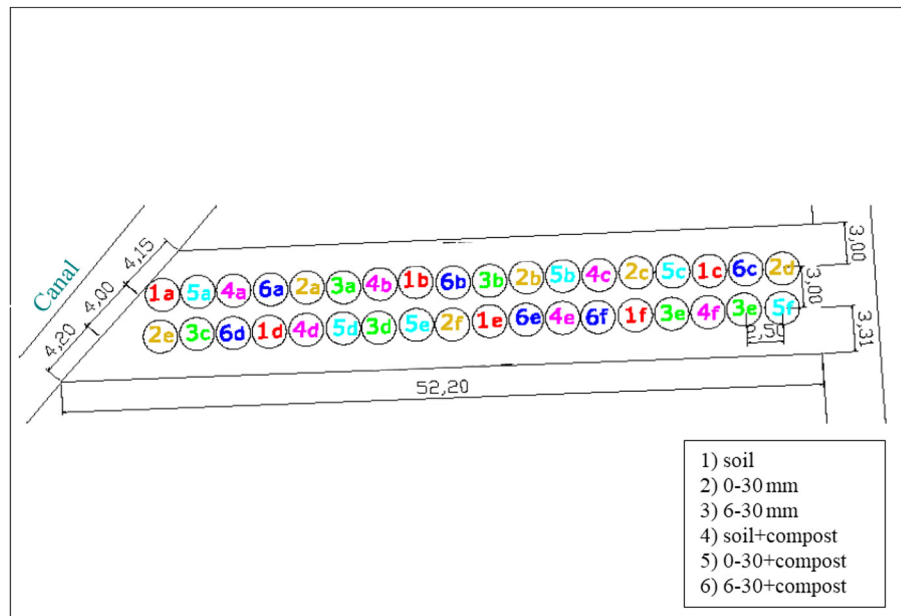


Fig. 1. Experimental set-up: numbers refer to treatments, and letters to replicates. Measurements are expressed in meters.

at 70° until reaching constant weight. The total length (primary + secondary roots) was then measured, and the dry biomass was determined on a precision weight scale.

2.4. Data analysis

The experiment was set up in a completely random design ($n = 6$). One and two-way ANOVA followed by Tukey's Multiple Comparison Test ($P \leq .05$) were performed to determine the statistical significant differences of the plant parameters. Statistical analyses were performed using R version 1.0.44 (R Foundation for Statistical Computing, Vienna, Austria).

3. Results

3.1. Substrate analysis

The water infiltration rate (K_f) and bearing capacity (E_{vd}) data are reported in Table 2. Texture significantly affected the water infiltration rate in both years of the experiment ($P = .003$ and $P < .001$ in the first and second years, respectively). The highest water infiltration was observed in the 6–30 substrate in the first year, in fact K_f was not measurable as the water percolated too quickly (the water immediately filtered into the ground when it was poured onto the plate, thus there were no measurable seconds before it disappeared), followed by the 0–30 substrate (9.33×10^{-6} m/s). The 6–30 substrates showed the highest value (5.27×10^{-5} m/s) also in the second year. The statistical interaction between the texture and compost did not affect K_f in either year.

The statistical interaction between the texture and compost significantly affected E_{vd} in the first year ($P = .033$). Higher values were reached in the crushed brick substrates without compost, especially in the 0–30 substrate (8.3 ± 0.15 MPa). However, the presence of compost decreased E_{vd} in 0–30 and 6–30 substrate textures (-21% and -22% , respectively), compared to the substrates without compost. In the second year, texture and compost individually affected E_{vd} ($P < .001$ and $P = .01$, respectively). An E_{vd} reduction was observed in all substrates when compost was applied. Without any compost, both the 0–30 and soil treatment showed higher E_{vd} values (11.4 ± 0.25 and 11.1 ± 0.85 MPa, respectively) than 6–30. However, the interaction between texture and compost did not significantly influence this

parameter (E_{vd}).

3.2. Tree growth analysis

In the C and NC treatments, the trunk diameter growth rates expressed as weighted values were, respectively: soil = 0.11 and 0.10; 0–30 = 0.18 and 0.18; 6–30 = 0.09 and 0.11. The two-way ANOVA did not show a significant effect of the different treatments (texture and compost).

Fig. 2 shows the results of the first and second years in terms of mean shoot length. The interaction between texture and compost significantly influenced the shoot length in the first ($P = .039$) and second year ($P = .005$).

In the first year (Fig. 3A), trees showed a similar shoot length in all the treatments. However, in the 6–30 substrate with compost, plants significantly showed lower (-34%) shoot lengths (3.5 ± 1.64 cm), compared to those growing on the 6–30 substrate without compost (5.3 ± 3.07 cm), although the standard deviation was wide (Fig. 3A). In addition, trees growing on the 6–30 substrate with compost had a shorter shoot length (5.5 ± 2.85 cm) than those in mixed 0–30 crushed bricks and compost substrates (3.5 ± 1.64 cm).

The interaction between texture and compost also significantly ($P = .005$) affected the shoot lengths in the second year (Fig. 3B). Trees growing in the 0–30 substrate, with and without compost, showed a higher mean shoot length (10.2 ± 3.65 cm and 8.2 ± 2.48 cm, respectively) than those in the soil (6.8 ± 1.71 and 6.3 ± 3.06 cm, C and NC, respectively) and in the 6–30 (5.2 ± 1.68 and 7.7 ± 4.11 cm C and NC, respectively) treatments.

The leaf chlorophyll index did not show significant differences between treatments in both year of the experiment (Table 3).

Fig. 4 reports the root growth parameters, measured at the final stage, in terms of length and biomass, only in the NC treatments, as reported in the Methods. Significant differences were detected for each treatment ($P = .0002$ for root dry weight; $P = .0008$ for total root length). Linden trees in the 0–30 substrate increased root biomass (733 ± 47.5 g DW) by 72% and 37% compared to the plants grown in soil (208 ± 84.0 g DW) and in the 6–30 substrate (469 ± 87.3 g DW), respectively. The roots of plants growing in both treatments showed a higher total length (1212 ± 154.5 and 789 ± 211.5 cm, in 0–30 and 6–30 respectively) than the plants growing in soil (272 ± 104.4 cm).

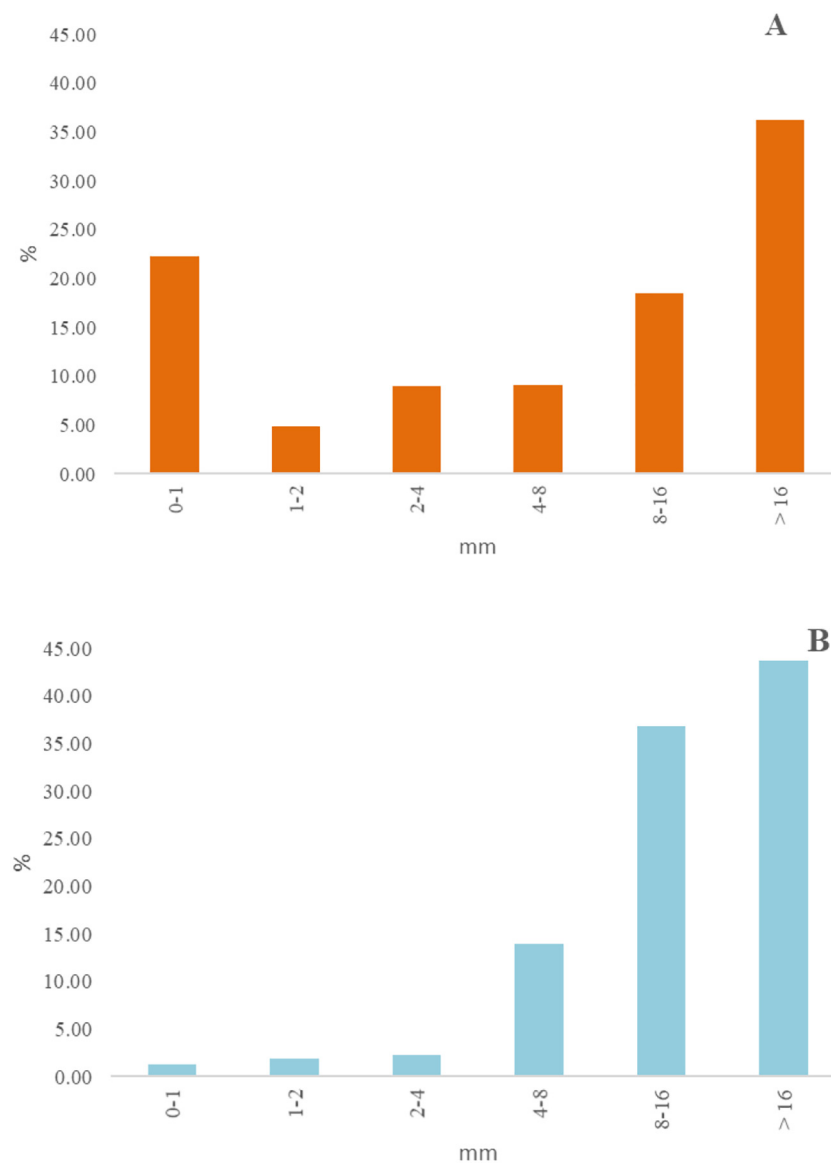


Fig. 2. Particle size distribution in 0–30 (A) and 6–30 (B) crushed bricks materials.

Table 1

Chemical properties of the original substrate materials.

Properties	Soil	Crushed bricks	Compost
pH	6.8	8.5	6.9
N tot (%)	0.15	0.06	2.5
C org (%)	0.85	0.43	27
P-ass (ppm)	5.05	4.95	120

4. Discussion

Our results showed that the effects of coarse texture substrates were positive in terms of the infiltration rate, bearing capacity, shoot length, and root development. The 0–30 texture substrate led to a better plant growth than the 6–30 treatment in terms of shoot and root development. The presence of fine particles, 0–1 mm, in the 0–30 crushed bricks material, facilitated the nutrient and water supply, as the fine particles create a better contact between the roots and soil, while the coarser particles, 8–16 and > 16 mm, counteracted the effect of compaction. This combination in the 0–30 mm texture resulted to be more effective for parameters such as substrate and growth of plants.

Table 2

The water infiltration rate (K_f) and bearing capacity (E_{vd}) measured for each treatment in the first and second years of the experiment. Data are followed by $\pm$ SD. Statistical significance was determined with two-way ANOVA followed by Tukey's Multiple Comparison Test ($P \leq .05$); * = $P < .05$, ** = $P < .01$, ns = not significant. Data followed by different letters are statistically different. n.d. = not detectable due to the rapidity of infiltration.

	K_f (m/s)		E_{vd} (MPa)	
	Year I	Year II	Year I	Year II
Compost				
Soil	3.58×10^{-7}	5.94×10^{-9}	$5.0 \pm 0.81c$	8.7 ± 0.60
0–30	9.33×10^{-6}	1.82×10^{-7}	$6.6 \pm 0.85b$	9.6 ± 0.70
6–30	n.d.	5.27×10^{-5}	$5.8 \pm 0.72c$	8.4 ± 0.32
No compost				
Soil	2.10×10^{-7}	3.82×10^{-8}	$5.3 \pm 0.94c$	11.1 ± 0.85
0–30	3.05×10^{-6}	2.21×10^{-7}	$8.3 \pm 0.15a$	11.4 ± 0.25
6–30	n.d.	4.62×10^{-8}	$7.4 \pm 0.92ab$	9.9 ± 0.85
Compost Texture	ns	ns	***	***
Compost $\times$ texture	***	***	***	*
Compost $\times$ texture	ns	ns	**	ns

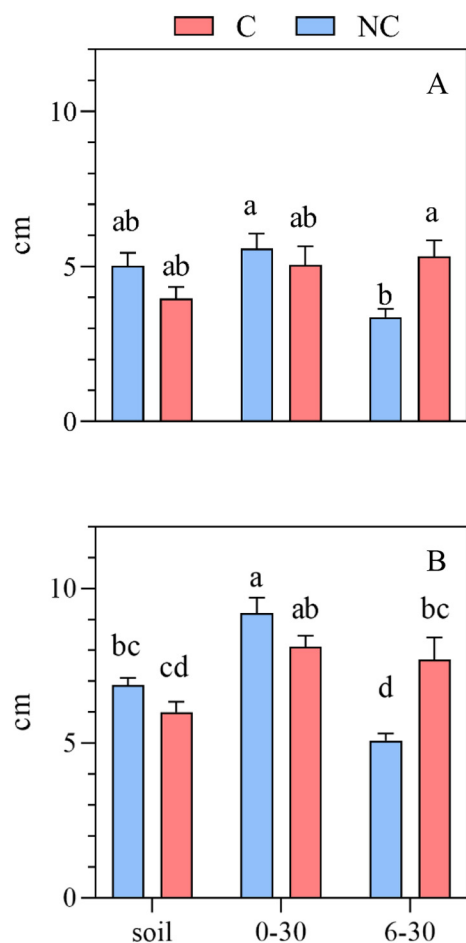


Fig. 3. Mean shoot length of *T. cordata* measured in the first (A) and second year (B) of the experiment for each substrate. Bars represent +SE. Statistical significance was determined with two-way ANOVA followed by Tukey's Multiple Comparison Test ($P \leq .05$); * = $P < .05$, ** = $P < .01$, ns = not significant. Data followed by different letters are statistically different. (C = compost; NC = no compost).

Table 3

Chlorophyll content index measured in *T. cordata* in the first and second year of the experiment for each substrate. Statistical significance was determined with two-way ANOVA followed by Tukey's Multiple Comparison Test ($P \leq .05$); ns = not significant.

	Chlorophyll content index	
	Year I	Year II
Compost		
Soil	41.6 ± 1.31	32.9 ± 3.00
0-30	40.8 ± 3.72	33.3 ± 5.33
6-30	41.8 ± 1.87	34.9 ± 2.64
No compost		
Soil	40.6 ± 5.01	33.9 ± 5.56
0-30	41.5 ± 2.67	27.4 ± 4.60
6-30	40.5 ± 1.06	35.5 ± 3.36
Compost	ns	ns
Texture	ns	ns
Compost × texture	ns	ns

Compost is compressible, and reduces the bearing capacity, when added to coarse substrates. The health status of the trees was not affected by the treatments, as indicated by the uniform values of the chlorophyll index.

The substrates comprised of crushed bricks had a greater capacity to resist compaction compared to the soil, although their bearing capacity

(11.4 MPa) did not reach the values required to bear the weight of vehicles (25 MPa) (Astleitner and Florineth, 2010).

The very high water infiltration rate of the 6-30 substrate suggests that too many large voids, in the absence of fine material, leave the soil profile dry and highly susceptible to drought. Substrates with too large voids, without irrigation, make the plants suffer due to water stress in hot seasons (Cannavo et al., 2018). The presence of fine particles in substrates, as in the 0-30 substrate, can affect the physical properties of the crushed bricks substrate, including the increase in water retention (Graceson et al., 2011).

The organic matter provided by compost reduced the bearing capacity due to its compressibility, creating a lithological discontinuity. Compost is often added to reduce soil compaction (Sæbø and Ferrini, 2006; McGrath and Henry, 2016) and to increase net primary productivity in soil rehabilitation (Layman et al., 2016). However, in the event of a critical load such as the action exerted by cars, the presence of organic matter can counteract the bearing capacity, and it is therefore necessary to differentiate the interventions focused to improve the soil requirements for roadside tree pits (Jim and Ng, 2018).

The effect of texture was statistically significant in all the treatments, showing that the soil was less water penetrable than the substrates. In addition, the coarse substrates were more effective at bearing loads than soil alone (Yilmaz et al., 2018). In fact, the texture significantly influenced E_{vd} and K_f during the experiment, due to the coarse matrix (Grabosky and Bassuk, 1995). The mix with a coarse texture (0-30) may prevent the compaction from increasing over time (Cannavo et al., 2018).

Shoot length values were very heterogeneous, reflecting the individual canopy architecture of each plant. This is especially the case when the plants are reproduced from seeds, leading to the genetic heterogeneity of the seedling phenotype. Some of the plants had many branches along the main axis, with many small buds and others had a few branches and big buds. During the vegetative periods, the first branches produced many short shoots whereas the second branches just had a few long shoots. The texture had a positive effect on the plants' vigor, expressed as shoot length, in 0-30 treatment. As mentioned above, the 0-30 mix included 22% of fine material (0-1 mm), which can help the particles' continuity, by improving the water movement and the nutrition availability. On the other hand, the higher development of the shoots in the 6-30 treatment without compost compared to the 6-30 with compost, could be a compensation symptom attributed to the stress that killed some of the other buds (Archibald and Bond, 2003).

The foliar chlorophyll index was uniform in the various treatments, indicating that the substrate treatments did not affect the general health status of the plants (Cinelli et al., 2004) although the treatments effects on shoot length and root development were significant, in line with Layman et al. (2010).

The chlorophyll index correlated with foliar N, thus giving a good estimate of the plant's nutritional status (Muñoz-Huerta et al., 2013). However, in the first year of the experiment before the transplant there may have been a residual nutritional effect of the fertilization carried out at the nursery. Nevertheless, the uniformity of the chlorophyll index values showed that the brick substrates can add useful elements for plant nutrition, and did not cause any nutritional deficiency (Nehls et al., 2013).

At the end of the experiment, the excavation of the plants highlighted that the coarse substrates led to an increased development of tree roots, related to the better circulation of oxygen and water in the rhizosphere (Kozłowski, 1999; Bühler et al., 2017). The plants grown in soil showed both the lowest biomass and root length. Anaerobic soil is usually associated with flooding or compaction of soil and commonly occurs in soils with a heavy texture, such as loamy soils with a high percentage of clay and silt (Kozłowski, 1999). The lower development and weight of the roots in the tested soil, which was mechanically impenetrable, highlighted that its compaction prevented the formation

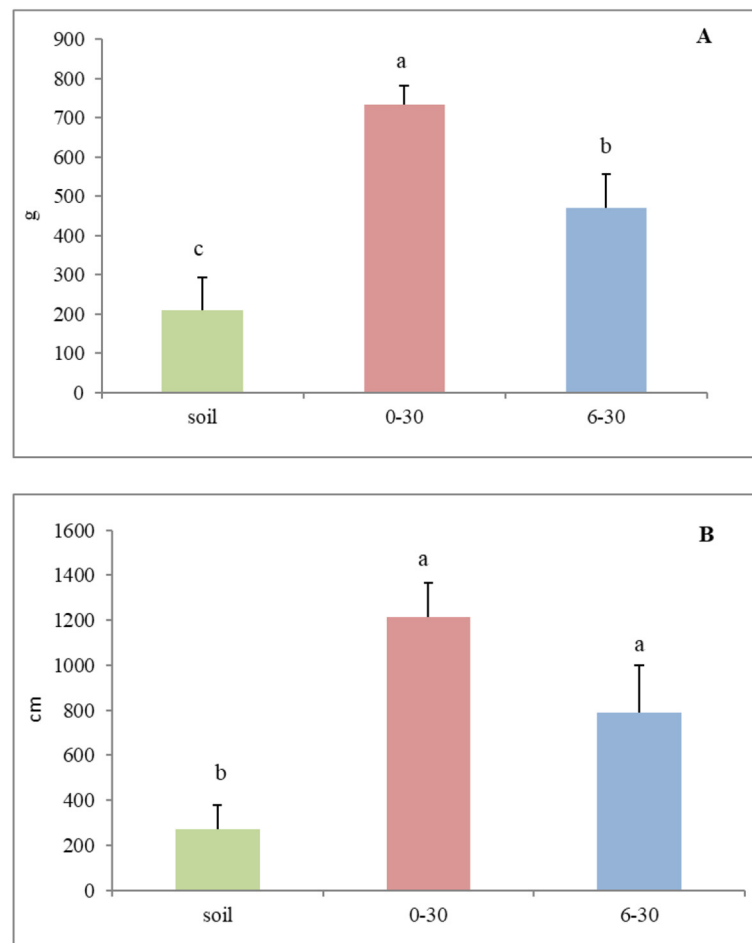


Fig. 4. Root dry weight (g) (A) and total root length (cm) (B) detected in *T. cordata* at the end of the experiment. Bars represent $\pm$ SD. Statistical significance was determined with one-way ANOVA followed by Tukey's Multiple Comparison Test ($P \leq .05$); * = $P < .05$, ** = $P < .01$, ns = not significant. Data followed by different letters are statistically different.

of large roots and their growth over the planting hole. Resistance to compaction is correlated to texture and moisture content: in a natural coarse matrix soil, moderate compaction increases the available moisture thus improving contact between the roots and the sources of nutrients (Kuss, 1986) necessary to promote root-soil interactions (Gregory, 2006). The 0–30 mix led to better conditions for root biomass compared to the soil and 6–30 substrate, and in terms of root length compared to soil, due to the balance of fine and coarse particles.

The skeletal substrates led to a better radical development (Yilmaz et al., 2018). This effect has been detected in linden trees (Bühler et al., 2017), which was found to be species specific (Bartens et al., 2010).

5. Conclusions

Of the various treatments, the coarse brick recycled material with a texture from fine to 30 mm, showed the best performance in linden tree establishment, in terms of infiltration rate, bearing capacity, shoot length and root development. Both coarse material substrates counteracted the compaction and presented a better water infiltration rate; while the addition of compost to the substrate reduced the bearing capacity. Although the lack of organic matter often represents a limit, the soil compaction for roadside trees is a serious problem to be faced, due to the high passage of people and vehicles, therefore the addition of compost in coarse substrates have a negative effect. The roots of the linden trees grown in coarse material substrates were longer and had a higher biomass. Coarse recycled materials facilitate a better air circulation and water drainage in the rhizosphere, and may be a valid

solution to reduce planting stress and thus help to establish roadside urban trees.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Archibald, S., Bond, W.J., 2003. Growing tall vs growing wide: tree architecture and allometry of *Acacia karoo* in forest, savanna and arid environments. *Oikos* 102, 3–14.
- ASA-SSSA, 1996. Methods of soil analysis, part 1 and 3. In: Physical and Chemical Methods, Second edition. ASA-SSSA, Madison, Wisconsin, USA.
- Astleitner, D., Florineth, F., 2010. Endbericht Baumsbstrat mit mineralischem Baustoff-Recycling-Material. Research Report Baustoff-Recycling-Verband BRV Wien. pp. 33. <http://www.baunat.boku.ac.at/fileadmin/data/H03000/H87000/H87400/Forschungsprojekte/Endbericht-Baumsbstrat-2010.pdf>.
- Bartens, J., Wiseman, P.E., Smiley, E.T., 2010. Stability of landscape trees in engineered and conventional urban soil mixes. *Urban For Urban Gree* 9 (4), 333–338.
- Bühler, O., Ingerslev, M., Skov, S., Schou, E., Thomsen, I.M., Nielsen, C.N., Kristoffersen, P., 2017. Tree development in structural soil—an empirical below-ground in-situ study of urban trees in Copenhagen, Denmark. *Plant Soil* 413 (1–2), 29–44.
- Cannavo, P., Guénou, R., Galopin, G., Vidal-Beaudet, L., 2018. Technosols made with various urban wastes showed contrasted performance for tree development during a 3-year experiment. *Environ. Earth Sci* 77 (18), 650.
- Cinelli, F., Tamantini, I., Iacona, C., 2004. Nutritional (Fe-Mn) interactions in 'Big Top' peach plants as influenced by the rootstock and by the soil CaCO_3 concentration. *Soil Sci. Plant Nutr.* 50 (7), 1097–1102.
- Craul, P.J., 1992. Urban soil in landscape design. John Wiley & Sons, Inc., NY.
- Day, S.D., Amateis, R.L., 2011. Predicting canopy and trunk cross-sectional area of silver

- linden (*Tilia tomentosa*) in confined planting cutouts. *Urban For Urban Gree*. 10 (4), 317–322.
- Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), *Methods of Soil Analysis: Part 1*, 2nd ed. Physical and Mineralogical Methods ASA-SSSA, Madison, pp. 399–404.
- Grabosky, J., Bassuk, N., 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. *J. Arboric.* 21 (4), 187.
- Graceson, A., Hare, M., Hall, N., Monaghan, J., 2011. Characterising the mineral components of green roof growing media. In: *First National Green Roof Student Conference*, Sheffield University, Sheffield, UK. Vol. 1.
- Gregory, P.J., 2006. Roots, rhizosphere and soil: the route to a better understanding of soil science? *Eur. J. Soil Sci.* 57 (1), 2–12.
- Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban soil compaction on infiltration rate. *J. Soil Water Conserv.* 61 (3), 117–124.
- Jim, C.Y., 2001. Managing urban trees and their soil envelopes in a contiguously developed city environment. *Environ. Manag.* 28 (6), 819–832.
- Jim, C.Y., Ng, Y.Y., 2018. Porosity of roadside soil as indicator of edaphic quality for tree planting. *Ecol. Eng.* 120, 364–374.
- Koeser, A.K., Gilman, E.F., Paz, M., Harchick, C., 2014. Factors influencing urban tree planting program growth and survival in Florida, United States. *Urban For Urban Gree* 13 (4), 655–661.
- Koolen, A.J., Rossignol, J.P., 1998. Introduction to symposium 19: construction and use of artificial soils. *Soil Tillage Res.* 47, 151–155.
- Kozłowski, T.T., 1999. Soil compaction and growth of woody plants. *Scandinavian J Forest Res* 14 (6), 596–619.
- Kuss, F.R., 1986. A review of major factors influencing plant responses to recreation impacts. *Environ. Manag.* 10 (5), 637–650.
- Layman, R.M., Day, S.D., Harris, J.R., Daniels, W.L., Wiseman, P.E., 2010. Rehabilitation of severely compacted urban soil to optimize tree establishment and growth. *Acta Hort.* 881, 505–509.
- Layman, R.M., Day, S.D., Mitchell, D.K., Chen, Y., Harris, J.R., Daniels, W.L., 2016. Below ground matters: Urban soil rehabilitation increases tree canopy and speeds establishment. *Urban For Urban Gree* 16, 25–35.
- Lorenz, K., Lal, R., 2009. Biogeochemical C and N cycles in urban soils. *Environ. Int.* 35 (1), 1–8.
- McGrath, D., Henry, J., 2016. Organic amendments decrease bulk density and improve tree establishment and growth in roadside plantings. *Urban For Urban Gree* 20, 120–127.
- Mullins, C.E., 1991. Physical properties of soils in urban areas. In: Bullock, Peter, Peter, J. (Eds.), *“Soil in the Urban Environment”*. Blackwell Scientific Publications, Gregory Edited by.
- Muñoz-Huerta, R., Guevara-Gonzalez, R., Contreras-Medina, L., Torres-Pacheco, I., Prado-Olivarez, J., Ocampo-Velazquez, R., 2013. A review of methods for sensing the nitrogen status in plants: advantages, disadvantages and recent advances. *Sensors* 13 (8), 10823–10843.
- Nehls, T., Rokia, S., Mekiffer, B., Schwartz, C., Wessolek, G., 2013. Contribution of bricks to urban soil properties. *J. Soils Sediments* 13 (3), 575–584.
- Ow, L.F., Ghosh, S., 2017. Urban tree growth and their dependency on infiltration rates in structural soil and structural cells. *Urban For Urban Gree* 26, 41–47.
- Passioura, J.B., 2002. Soil conditions and plant growth. *Plant Cell Environ.* 25 (2), 311–318.
- Pregl, O., 1999. *Handbuch der Geotechnik, Band 9: Wasser im Untergrund*. Eigenverlag des Institutes für Geotechnik Univ. für Bodenkultur, Wien.
- Rahman, M.A., Moser, A., Anderson, M., Zhang, C., Rötzer, T., Pauleit, S., 2019. Comparing the infiltration potentials of soils beneath the canopies of two contrasting urban tree species. *Urban For Urban Gree* 38, 22–32.
- Sæbø, A., Ferrini, F., 2006. The use of compost in urban green areas—a review for practical application. *Urban For Urban Gree* 4 (3–4), 159–169.
- Sand, E., Konarska, J., Howe, A.W., Andersson-Sköld, Y., Moldan, F., Pleijel, H., Uddling, J., 2018. Effects of ground surface permeability on the growth of urban linden trees. *Urban Ecosyst.* 21 (4), 691–696.
- UNI EN 933-1, 1999. Prove per determinare le proprietà geometriche degli aggregati - Determinazione della distribuzione granulometrica - Analisi granulometrica per stacciatura.
- Yilmaz, D., Cannavo, P., Séré, G., Vidal-Beaudet, L., Legret, M., Damas, O., Peyneau, P.E., 2018. Physical properties of structural soils containing waste materials to achieve urban greening. *J. Soils Sediments* 18 (2), 442–455.