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Tree development in structural soil – an empirical below-ground in-situ study of urban trees in Copenhagen, Denmark

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Abstract

Aims The purpose of this study is to evaluate root and stem growth, nutrient status and soil properties of a tree planting in structural soil.

Methods Root and stem growth were measured at an 10-year-old urban planting of *Tilia* x *europaea* L. 'Pallida' established in structural soil on a paved square in Copenhagen, Denmark.

Root abundance was quantified and soil profiles were established at three different distances from 10 trees (1.0, 1.9, and 2.9 m). Soil and leaf samples were analysed for nutrient concentrations.

Results Abundant root presence was measured across the entire profile of structural soil (160×60 cm) at all distances, provided that structural soil layers were constructed correctly. Erroneously constructed structural soil layers however, resulted in impaired tree and root growth. Coarse root morphology was affected by the confined growing space in the voids of the stone matrix. The soil was relatively alkaline with an average pH ($CaCl_2$) of 7.3. Foliar analysis revealed deficiencies of K and Mn. These deficiencies might be due to a combined effect of high pH and low soil concentrations of these nutrients.

Conclusions The study documents that correctly constructed structural soils allow and encourage root growth in load bearing layers.

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Introduction

Trees in urban areas have many beneficial effects ranging from aesthetic and architectural functions to the interception of solar radiation, carbon sequestration and air quality improvement (e.g. Georgi and Zafiriadis 2006; Hardin and Jensen 2007; Nowak and Crane 2002).

However, it can be challenging to establish good growth conditions for trees at urban sites, especially in paved environments. As a result, urban trees often express reduced vitality and have a lower life expectancy compared to trees in more favourable growth conditions (e.g. Balder et al. 1997). A major reason for this is unfavourable soil conditions: The low soil volume available for root growth and nutrient uptake, often limited by highly compacted load bearing layers under paved

surfaces, is an important factor (Bühler et al. 2009). According to Kristoffersen (1998), heavy soil compaction in load bearing structures often limits the space for root growth to the soil of planting pits. In Denmark, bulk density of road and pavement foundations often exceeds 2 g/cm^3 (Kristoffersen 1999). This level of compaction has been shown to restrict root and shoot growth for many woody species in most soil types (Alberty et al. 1984, Day and Bassuk 1994, Day and Amateis 2011, Fair et al. 2012), suggesting that traditional load bearing layers for pavements are an unsuitable environment for growth of tree roots.

Structural soil is an establishment method that is supposed to allow root growth in load bearing soil structures by creating a stone matrix, which transfers the load from the paved surface to the subsoil (Grabosky and Bassuk 1995). Voids between stones are filled with a growth media, allowing roots to explore the stone/soil matrix. As an additional benefit, structural soils may reduce the occurrence of root growth damage to sidewalks as described by Nicoll and Armstrong (1998), as structural soils facilitate root growth into deeper soil layers.

In experimental plantings, Kristoffersen (1999) found that growth rates of trees in structural soils were similar to growth rates of trees grown exclusively in topsoil. Grabosky et al. (2001) report increased shoot growth and root extension of trees established in structural soils compared to trees established in a standard pavement profile, and Bühler et al. (2007) report similar findings studying urban tree plantings in Copenhagen, Denmark. Also in France, positive results for tree development in structural soils have been observed (Lemaire and Sorin 1997). However, Smiley et al. (2006) found significant reductions in growth rates when comparing trees grown in structural soil with trees grown in uncompacted soil but covered with suspended paving.

Creating favourable conditions for root growth of urban trees is not only a question of satisfactory growth of the above ground biomass, but also has a crucial influence on tree stability, the risk of tree failure and subsequent potential damage to people and/or property. Nicoll et al. (2006) found that deep rooting increased critical turning moments of trees under wind pressure. Although dependent on tree species, landscape trees planted in structural soils are less prone to uprooting compared with trees in conventional planting pits due to enhanced root development (Bartens et al. 2010).

In urban areas, soil is often relatively alkaline due to the deposition of alkaline particles from construction activities, pavement and asphalt, affecting plant availability of nutrients and causing nutrient deficiencies and imbalances (Messenger 1986, Jim 1998a, b, Urban 2008)

The nutritional status of urban trees in general and trees established in structural soil specifically is an area that is only marginally investigated by research. Soil fertility in urban areas is often characterized by high heterogeneity, and threshold values for nutritional conditions lack or need to be approximated from related crop systems (Sloan et al. 2012, Cekstere and Osvalde 2013).

The main purpose of the paper

Recent investigations have mostly been based on above-ground assessments of vitality and growth and/or on experimental plantings. The presented study addresses the paucity of information on tree development and root distribution in structural soil through an in situ investigation carried out in an urban tree planting initiated by the local municipal authority. The study site thereby reflects actual municipal tree planting procedures. As the trees had to be removed due to the construction of a city metro network, destructive measurements of trees and soil were possible.

The purpose of this study was to analyse root and stem growth, nutrient status and soil properties of a tree planting in structural soil.

Due to a construction error in one of the two bands forming the planting pattern in the square, an opportunity arose to make direct comparisons of trees of *the same species* established *in the same planting* space *with* and *without* correct establishment of a structural soil layer.

The hypotheses of the study were:

1. Structural soils enable widespread growth of roots in load bearing structures.
2. Physical and chemical soil conditions in structural soils enable sufficient and vital growth of trees.
3. Concentrations of nutrients in the soil are affected by the distance to the trees, so that nutrient concentration will be lower closer to the trees due to nutrient uptake and root exploration.
4. Foliar analyses will not reveal nutrient deficiencies.

Materials and methods

The planting of *Tilia x europaea* L. 'Pallida' (grafted on unspecified seedling rootstocks of *Tilia platyphyllos* SCOP.) was carried out in June 2001 in the square of Kongens Nytorv, Copenhagen (N 55° 40.832′, E 12° 35.156′, WGS 84). At the time of planting, the trees had a stem circumference of 30–35 cm at 1.0 m stem height. In total, 80 trees were planted in planting pits connected by two concentric elliptical bands of structural soil, referred to in the following text as the inner and the outer band (Fig. 1).

During the first 3 years after planting, the trees were irrigated on a regular basis.

The establishment of the structural soil bands

The structural soil bands between the planting pits had a width of 1.6 to 2.0 m, a length of 7–8 m and a total depth (including the paving) of 80 cm. From top to bottom the

Fig. 1 Aerial picture of the tree planting at Kongens Nytorv. The two ellipses of trees are planted in connected structural soil bands. Test trees are encircled. Picture supplied by the Municipality of Copenhagen

construction consisted of cobblestone-paving in a bedding layer of well graded sand in a depth of 0–20 cm, then, separated by a geotextile, a layer of structural soil in the depth of 20–80 cm and finally compacted subsoil from 80 cm and deeper. Paving material was granite cobblestones of approximately $10 \times 10 \times 10$ cm, joints had a width of approximately 1 cm and were filled with well graded sand (cf. bedding material). The joint area was estimated to account for 15–20 % of the paved area.

The structural soil was constructed using stones with a diameter between 64 and 150 mm and harped topsoil in the voids between the stones. It was constructed in three sublayers of 20 cm each, where the first layer was established on the subsoil (i.e. the bottom of the planting pits). The stone layer was compacted using a vibratory plate compactor. Then 3 cm of topsoil was dispersed and swept into the voids. This procedure of laying out topsoil was repeated four times for each of the three 20 cm sublayers. After completion of the topmost sublayer, the entire construction was watered thoroughly.

The installation was equipped with a drainage pipe below the structural soil layer and a combined irrigation and aeration pipe in the topmost structural soil layer. The actual planting pits were not constructed with structural soils, but had an open surface area of 1.5×1.5 m and a soil volume of 1.4 m^3. The structural soil band connecting the planting pits contributed with a total volume of approximately 6.3 m^3 per tree. Estimating a soil:stone ratio of 1:3 in the structural soil, approximately 1.6 m^3 of this total volume is soil. As a result, the total available soil volume per tree was approximately 1.4 m^3 + 1.6 m^3 = 3.0 m^3.

A construction error in the structural soil of the outer band

In the examined part of the outer band, a layer of gravel mixed with construction garbage (clay lumps and concrete pieces – often smaller than 2 cm) was observed. The layer was situated in the middle of the structural soil layer, the thickness of the layer varied between 2 and 20 cm (most frequently between 5 and 15 cm). The top of this layer was 50–60 cm from the surface of the pavement. The thickness of the layer apparently increased with increasing distance from the trees. No load bearing stones were found in this layer, and the soil appeared heavily compacted. In the text below, this layer in the outer band is referred to as a construction error.

Trees selected for the study

In September 2010, 10 of the remaining 60 trees (20 were already removed) in the square were selected, based on the following criteria:

- Equal number of trees in inner and outer band
- Adjacency of trees
- Uniformity of trees
- Availability of storage area for soil and pavement materials

Height and circumference (girth) measurements of the trees

In the autumn of 2011, tree height and stem circumference 1.0 m above ground level were measured on all trees on the square with a Vertex IV ultrasound two point height measuring system and a measuring tape, respectively.. Earlier stem circumference measurements were available from 2005, for all trees in the square, and from 2010 for the 10 test trees only. At the time of planting in 2001, stem circumference in 1.0 m stem height was supposedly 30–35 cm (based on nursery specifications).

In addition, annual ring width was analysed. For each of the 10 selected trees, one stem disk was taken at a height of 1.3 m. The disks were numbered and the east/west-orientation was marked. The width of the annual rings were then measured using a stereo microscope with a measuring ocular (precision = 0.05 mm). Measurements were carried out on the east and west sides of each disk. Average annual ring width development was then computed for each tree and averaged for all 10 trees.

Soil analyses

In the survey, a description of the physical properties of the soil was made based on profiles excavated using a digger in November 2011. The resulting profiles were more than 1 m in depth and had a width of 2 m. Soil samples were obtained from vertical transects at distances of 1.0 and 2.9 m from both sides of the trees (Fig. 2). The soil was sampled in two depths, 20–50 and 50–90 cm, respectively. In total, 8 soil samples per tree were collected. Subsequently, samples taken from the same depth

and same distance from a given tree, but from opposite sides of the tree, were pooled, resulting in a total of 40 soil samples. In addition samples were taken from gravel surrounding drainage tubes.

Texture analysis was made by wet sieving and sedimentation of soil samples, including one from the nursery that produced the trees. For each tree, soil of the relevant individual samples was pooled together into one main sample. The texture classes used were: humus, clay (<0.002 mm), silt (0.002–0.02 mm), fine sand (0.02–0.2 mm) and coarse sand (0.2–2.0 mm). Determination of soil density and degree of compression were based on visual observation, as it was impossible to obtain larger intact samples from structural soils.

For the chemical analyses, soil samples were dried at 55 °C until constant weight (2–4 days). Clods of earth were gently, but coarsely ground to a particle size less than 2 mm. Chemical analyses were carried out on subsamples. Soil samples were extracted with 1 M NH_4NO_3 (Stuanes et al. 1984) and the extracts were analysed for the concentration of exchangeable cations of K, Ca, Mg, Fe, Mn and Na by ICP-OES (Perkin Elmer, Optima 2000). The concentration of water-soluble Na and Cl was measured in a soil water solution by ICP-OES (Perkin Elmer, Optima 2000). The total concentration of C and N was also measured (C/N analysator SNCPrimacs). Soil samples were analysed for the concentration of H_2SO_4 (0.1 M) extractable P (Plantedirektoratet 1994). Loss on ignition (LOI) was determined after heating to 400 °C. The cation exchange capacity (CEC) and base saturation (BS) were calculated as described in ICP Forest (2010), and the exchangeable acidity (EA) was measured on the basis of titration (METLER Toledo T50), and calculated as described in ICP Forest (2010). The soil pH was measured for soil samples in a 1:5 soil:water ratio by Meterlab, PhM standard pH meter (electrode: Radiometer analytical, type Combined pH Electrode Red Rod pHC2401-8), and in a $CaCl_2$ (0.01 M) soil solution using the same instruments (ICP Forest 2010). All concentrations of solid material refer to dry weight at 55°C.

Root distribution analyses

The vertical and horizontal position of the roots in the profile were determined using a flexible measuring grid with 10×10 cm fields (Fig. 3). The diameter of coarse roots (lignified, diameter >1 mm) was
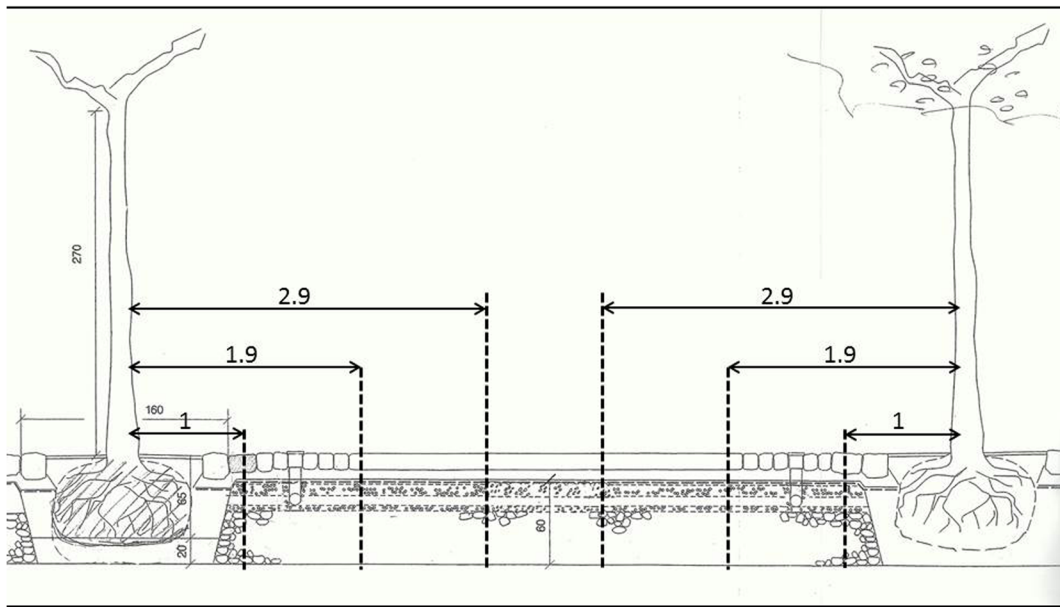
Fig. 2 Longitudinal section cut of the planting stripe, designating soil profile positions for soil samples (1 and 2.9 m) and root measurements (all distances) Distances of soil profiles to trees indicated in m

measured with an electronic calliper, while the amount of fine roots was assessed using a classification scale from 0 to 3 (Table 1). Root distribution was surveyed in profiles excavated at distances of 1.0, 1.9 and 2.9 m from both sides of the trees amounting to 6 samples per tree (Fig. 2). Measurements and assessments were carried out over the entire profiles covering the cross section of the structural soil bands. The upper 20 cm were separated from the structural soil layers by geotextile, and only in very few cases the closest soil profile to the tree (1.0 m) revealed root presence above a depth of 20 cm.

Fig. 3 Measurement setup with grid for root measurements in soil profile. Dimension of squares = 10 × 10 cm

Foliar analyses

For foliar analysis, 10 leaves were collected from each tree from non-shaded south facing branches on August 10, 2011. Foliar samples were dried at 55 °C until constant weight was reached. Dry weight of each single leaf was documented. Leaves from each respective tree were then pooled, ground and used for chemical analyses. The concentration of N and C were determined by infrared absorption spectroscopy (IR) after dry combustion in an oven (LECO-CNS 2000). Subsamples from each tree were digested in nitric acid (HNO_3) in PTFE bombs in a microwave oven (CEM, DMS-2000). The concentrations of P, K, Ca, Mg, S, Fe, Mn, Zn and Na were measured by inductively coupled plasma atomic emission spectroscopy ICP-AES (Perkin Elmer, optima 3000 XL). All subsequent concentrations of solid material refer to dry weight at 55 °C.

Table 1 Description of the scale for assessing the amount of fine roots in the soil fraction

Value	Interpretation
0	No fine roots in measuring field
1	1−5 fine roots in measuring field
2	5 or more fine roots in measuring field
3	Many dense fine roots

Data analysis

Data from foliar and soil analyses were analyzed based on an analysis of variance and tested for differences between bands and, for soil data, also for distance to tree and sample depth with a significance level of at least 95 % (*$P < 0.05$) (OriginLab V. 8.1: ANOVA). Annual ring measurements were analyzed for significant differences between means of the two bands, using Bonferroni multiple comparison analysis (SAS 9.3) with a significance level of at least 95 % (*$P < 0.05$). Measurements of tree height, stem circumference and root distribution were analyzed and tested for differences between the bands based on a linear mixed model approach (MIXED procedure in SAS 9.2). Uniformity of variance was tested by visual inspection of residual plots produced with the SAS procedure GLM (SAS 9.3).

The statistical analyses of root distribution were affected by a high degree of variation among the individual trees, requiring a logarithmic transformation of data before further statistical analyses could be carried out.

Results

Circumference and height measurements of trees

For the 10 selected trees, average circumference increased from 41.8 to 62.7 cm in the period of 2005 to 2011 (Table 2). The selected trees in the inner band had an average circumference of 43.8 cm in 2005 compared to 39.8 cm for the trees in the outer band – i.e. there was a difference of 4.0 cm. In 2011, this difference had increased to 7.2 cm in favour of the trees in the inner band. . Differences in stem circumference means between the inner and outer band were only statistically significant for the ten selected trees. Tests comparing the inner and outer band measurements including the entire planting could not detect significant differences between the bands.

Regarding height, the average for the selected trees in 2011 was 8.9 m with no significant differences between height means when comparing trees in the inner band with trees in the outer band (Table 2).

After establishment in 2001, the average annual ring width for the selected 10 trees ranged from a minimum of 0.8 mm in 2002 to a maximum of 7.6 mm in 2007 (Fig. 4). The average annual ring width from establishment to the time of felling (2002–2011) was 4.1 mm. There was a clear difference between annual ring width of the trees in the inner and outer band, corresponding to the circumference measurements. The trees in the inner band had an average annual ring width of 4.7 mm, while the trees in the outer band had an average of 3.6 mm. Differences were statistically significant in the years 2005, 2006 and 2010 ($P < 0.05$), while in 2004, 2007 and 2009 differences approached significance ($P < F$ 0.077, 0.063 and 0.051, respectively).

After transplantation from the nursery to the final site, average annual ring width decreased from 8.7 mm in 2001 to 0. 8 mm in 2002, indicating a severe

Table 2 Stem circumference (measured at 1 m trunk height) and height of trees (mean ± standard deviation). Circumference measurements were carried out after the end of the growth season for all trees in 2005 and 2011, in 2010 for the 10 selected trees only.

Tree height was only measured in 2011. Means differ significantly between outer and inner band when followed by different letters ($P < 0.05$)

	Entire planting			Selected trees[d]		
	All trees[a]	Outer band[b]	Inner band[c]	All trees	Outer band	Inner band
Stem circumference [cm], autumn 2005	43.0 (±4.7)	43.6 (±3.9)	42.3 (±5.9)	41.8 (±3.0)	39.8 (±1.7)a	43.8 (±2.7)b
Stem circumference [cm], autumn 2010	n.a.	n.a.	n.a.	59.8 (±4.6)	56.2 (±1.3)a	63.4 (±3.6)b
Stem circumference [cm], autumn 2011	63.0 (±7.9)	61.1 (±8.2)	64.7 (±7.4)	62.7 (±5.3)	58.9 (±2.5)a	66.6 (±4.6)b
Height [m], autumn 2011	8.8 (±0.7)	8.7 (±0.7)	8.8 (±0.7)	8.9 (±0.5)	8.7 (±0.4)	9.1 (±0.6)

[a] In 2005 measurements covered 80 trees, in 2011 60 trees

[b] In 2005 measurements covered 40 trees, in 2011 29 trees

[c] In 2005 measurements covered 40 trees, in 2011 31 trees

[d] A total of 10 trees were selected; 5 in the inner band and 5 in the outer band

Fig. 4 Average annual ring width of the trees in the inner band and the outer band. Error bars denote standard deviation. Measurements marked by a star (*) indicate that the means of the two bands are statistically significant different ($P \leq 0.05$)
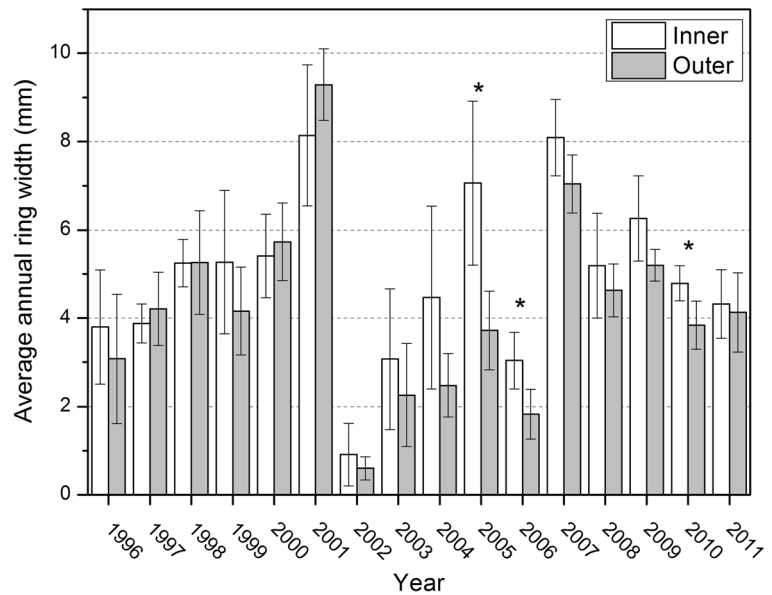
transplant shock reaction. In 2005, trees had regained approximately the same level of stem increment as prior to transplantation. Trees in the inner band recovered faster compared to trees in the outer band (Fig. 4). In the years before transplantation, no systematic differences in annual ring width could be observed between the trees later planted in the different bands.

Soil analyses

Excavation of soil profiles revealed a stone matrix with voids completely filled with soil in all depths. On the other hand, no obvious signs of compaction of the soil fraction were observed, except in the wrongly constructed section of the outer band. Soil odour and colour generally indicated aerobic conditions in soil profiles, except for one single tree. In this case, the deeper layers of the excavated profile (2.9 m from the tree) revealed a faint smell of hydrogen sulphide (H_2S), indicating anaerobic or oxygen poor conditions. In this part of the soil profile the soil lacked stones (as structural material) and appeared compacted, possibly due to repair works on underground cables. Standing water was observed only in one single planting pit, at a distance of 2.9 m from the tree.

Texture analysis revealed that the sand fraction accounted for over 80 % of the soil, while soil fractions with finer particles (clay and silt) constituted 5–15 % (all results percentage by weight, Table 3). Organic materials accounted for 3–4 %. The clay fraction was

significantly larger in the inner band compared to the outer band. On the other hand, the coarse sand-fraction was significantly smaller in the inner band. This was most likely due to the incorrect construction of the outer band (gravel etc.) (Table 4).

The level of pH in the soil was high compared to the recommended values (Table 4). In general, the soil contained enough nutrients to support (further) tree

Table 3 Distribution of the soil into texture classes (percentage by weight).* indicate significant differences between mean values of inner and outer band ($P < 0.05$)

Share of soil fraction [wt%]	Mean	Min.	Max.
Organic fraction			
Inner band	3.5	3.3	3.8
Outer band	3.5	3.2	3.9
Clay (<0.002 mm)			
Inner band	6.4*	5.2	7.5
Outer band	4.9*	3.9	6.1
Silt (0.002–0.02 mm)			
Inner band	5.8	4.4	7.3
Outer band	5.2	1.4	7.6
Fine sand (0.02–0.2 mm)			
Inner band	32.7	30.7	35.1
Outer band	30.0	27.2	34.0
Coarse sand (0.2–2 mm)			
Inner band	51.8*	49.6	53.7
Outer band	56.4*	54.6	58.2

Table 4 Main results of the chemical soil analyses. * indicates significant differences on a 5 %-level between mean values of inner and outer band. The analyses included 40 soil samples

	Mean	Min.	Max.	Recommended interval
Total analyses				
C [g/kg]	20.9*	15.1	26.7	
N [g/kg]	0.919*	0.480	1.231	
C:N ratio	23.6*	18.0	35.7	
Phosporus				
P (H$_2$SO$_4$) [mg/kg]	340	156	676	180–240[a]
Exchangable cations				
K [mg/kg]	59.7*	36.6	97.3	70–100[a]
Ca [mg/kg]	4309*	3913	4691	1000–2000[a]
Mg [mg/kg]	45.0*	24.7	88.5	50–80[a]
Fe [mg/kg]	0.545	<0.25	0.980	2–6[a]
Mn [mg/kg]	5.22*	2.37	10.81	10–25[a]
Na [mg/kg]	35.6	6.2	103.1	
Salt				
Na(H$_2$0) [mg/kg]	63.2	21.3	120.3	
Cl(H$_2$0) [mg/kg]	9.66	<2	44.3	
pH				
pH(CaCl$_2$)	7.26	6.77	7.49	5.3–6.5[a]
pH(H$_2$O)	8.00*	7.31	8.34	5.5–7.0[c]
CEC^2 and BS[b]				
CEC [cmol(+)/kg]	22.2*	20.0	24.3	
BS [%]	99.9	99.8	100.0	
Organic matter				
LOI^2 [%]	2.24*	1.18	3.04	

[a] According to local Danish recommendations from Holgersen (1994), Jørgensen et al. (2011) and Bühler (2012). Even though the recommended values for some of the exchangeable cations were measured using different extractions, they are used here for interpretation of the level of magnitude

[b] *CEC* Cation exchange capacity, *BS* Base saturation, *LOI* Loss on ignition

[c] Urban (2008)

growth. However, the nutrients K, Mg, Fe and Mn were not present in recommended concentrations, on the other hand, the concentrations of Ca were notably higher. The analyses of Al and exchangeable acidity (EA) produced values below the detection threshold, which was in accordance with the high (alkaline) soil pH.

The results suggested that the difference in construction of the two bands also affected the chemical soil properties. Soil sampled at the maximum depth and distance from the trees revealed a significantly higher concentration of C, N, K, Ca, Mg, Mn as well as a significantly higher CEC and LOI in the inner band, while the C/N ratio and pH(H$_2$O) were significantly lower. The best growth conditions in terms of nutrient concentrations were found in the inner band.

Nutrient concentrations were in general unaffected by the distance from trees, with the exception of C, N and Ca in the upper soil layers in the inner band.

Root distribution analyses

At all analysed depths and distances from trees, fine and coarse roots were found (see Figs. 5, 6 and 7). For coarse (lignified) roots, average root diameter as well as cumulative basal area of roots decreased with increasing distance from trees. At a distance of 1.0 m, the average diameter was 2.4 mm, which decreased to 1.0 mm at a distance of 2.9 m. Over the same interval the cumulative basal area decreased from 30 to 5 mm^2/dm^2. However, while the decrease of diameter was gradual, the basal area declined sharply from 1.0 to 1.9 m, before levelling off between 1.9 and 2.9 m.

The density of fine roots also decreased with increasing distance from the trees. At a distance of 1.0 m, roots were observed in nearly 80 % of the profile area. At 2.9 m, fine roots could still be found in approximately 50 % of the profile areas. The fine root density decreased most notably at a larger distance from trees compared to the coarse root basal area. At 1.0 m from trees, the density of fine roots was 8 roots/dm^2 falling to 4 roots/dm^2 at 2.9 m from trees. In general, larger coarse roots showed clear signs of deformation caused by the limited size of the voids between the stones in the structural soil. There were no signs of wounds, but secondary growth had clearly been impaired.

Root presence in the inner band was found to be significantly larger compared to root growth in the outer band in particular in terms of root growth in the deeper structural soil layers (Fig. 5). In the inner band, coarse roots were present across the entire profile with a maximum basal area at a depth of 60 cm. In contrast, in the outer band the maximum was reached at a depth of 40 cm. Furthermore, analyses show that root basal area was highest in the inner band, peaking at approximately 80 mm^2/dm^2 (at 1.0 m distance) compared to around 60 mm^2/dm^2 in the outer band. In general, fine roots were also found across the entire profile. Regarding fine root densities, band differences were most noticeable at a distance of 2.9 m, where fine roots were less abundant
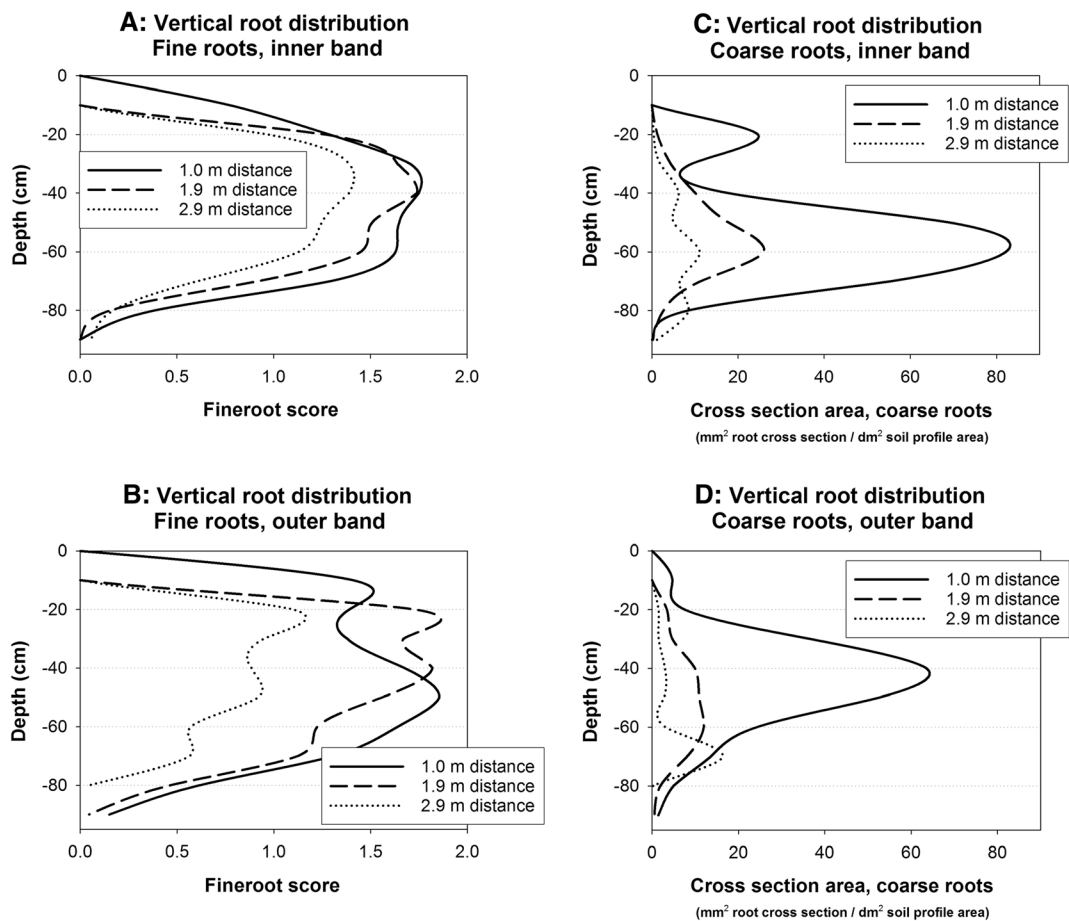
Fig. 5 Vertical distribution of roots for the inner and outer band of trees – fine roots (**a**, **b**) and coarse roots (**c**, **d**)

in the outer band, while concurrently confined to the upper half of the profile (Fig. 6). For coarse roots the pattern was similar, although less obvious (Fig. 7). In fact, there were areas in the outer band where roots were completely absent.

Roots were observed in close proximity to ventilation pipes and/or drainage pipes. Coarse roots tended to cluster, while fine roots were more evenly distributed throughout profiles. In certain profiles, no or limited root presence was observed in the upper 30–40 cm along profile edges.

Foliar analyses

Analyses of leaf weight and concentration of chemical compounds showed no significant differences between the inner and outer band.

The measured concentrations (Table 5) revealed that the trees did not suffer from deficiencies of N, P, Ca,

Mg, Fe, Zn and S when compared to threshold values (van den Burg 1985, 1990). However, K and Mn deficiencies were detected, when compared to the literature values. This corresponds to the measured concentrations of these two nutrients in the soil. The low foliar concentration of Mn corresponds to the high soil pH, however visual deficiency symptoms were not obvious for K or Mn (Mn deficiency: pale green leaves and K deficiency: yellowing and necrosis of the leaf margins, beginning on the lower and shaded leaves).

Discussion

The results show that good conditions for root growth of urban trees were provided where structural soil was constructed correctly. Root presence was observed over the entire soil profile area, as well as at all measured distances from the trees, with the majority of roots
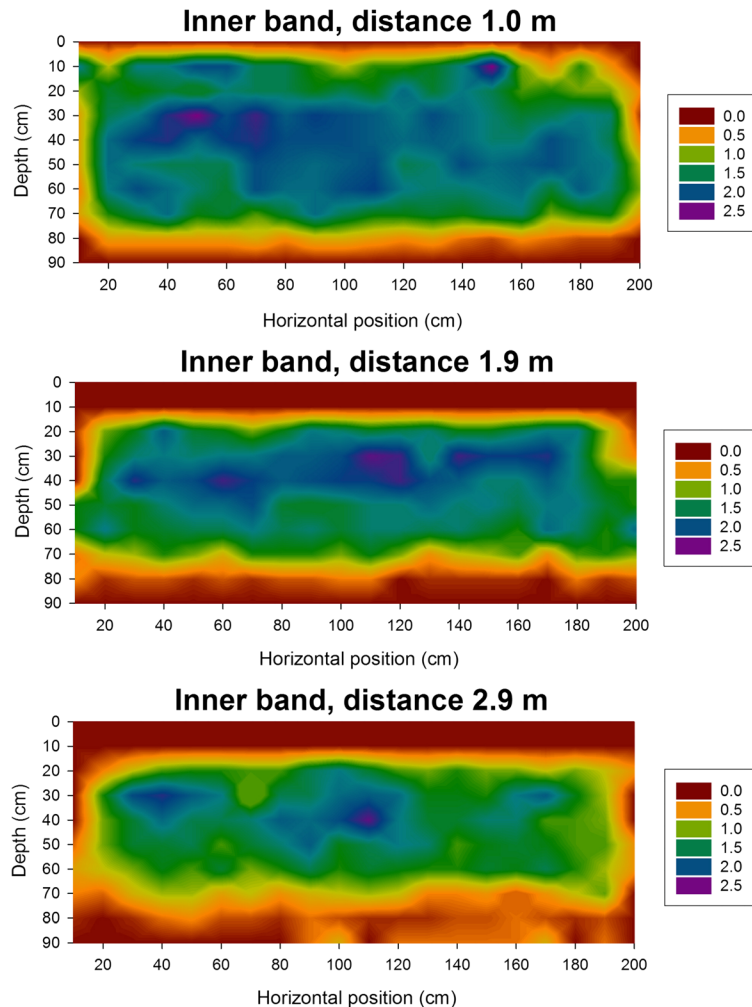
A: Fine roots (<1 mm), inner band

Inner band, distance 1.0 m

Inner band, distance 1.9 m

Inner band, distance 2.9 m

Fig. 6 Contour plots of the distribution of fine roots for the inner band (**a**) and the outer band (**b**) of trees. The vertical position is measured from the upper edge of the paving, horizontal position is located within a 2.0 m distance from the stem. Differences in root presence and distribution between the correctly and the erroneously constructed soil bands occurred and were most pronounced at large distances from the trees (2.9 m), where the compacted gravel layer was also most prominent, indicating that tree roots experienced difficulties penetrating this layer. In a limited number of profiles, root presence was restricted to the upper 30–40 cm along the profile edges, probably due to the presence of concrete residues from unspecified infrastructure (e.g. backing-up of kerbstones).

Determination of nutrient requirements, fertilization and nutrient status of trees have been discussed in forest measured from the edges of the structural soil layer, where 0 is pointing towards the middle of the elliptical bands

research for a century and Tamm (1964, 1968) and Tamm et al. (1999) provide a good overview of the findings. It has been recognised that the nutrient status of trees is best assessed by foliar analysis compared to soil analysis. However, chemical soil analysis (e.g. concentration of exchangeable nutrients, CEC, BS and pH) combined with information regarding the general soil condition (e.g. texture, water saturation, compaction and porosity) may provide important information on the amount and availability of nutrients in the soil.

van den Burg (1985 and 1990) compiled a large number of studies on foliar analysis and threshold values for nutrient status and deficiencies in trees,
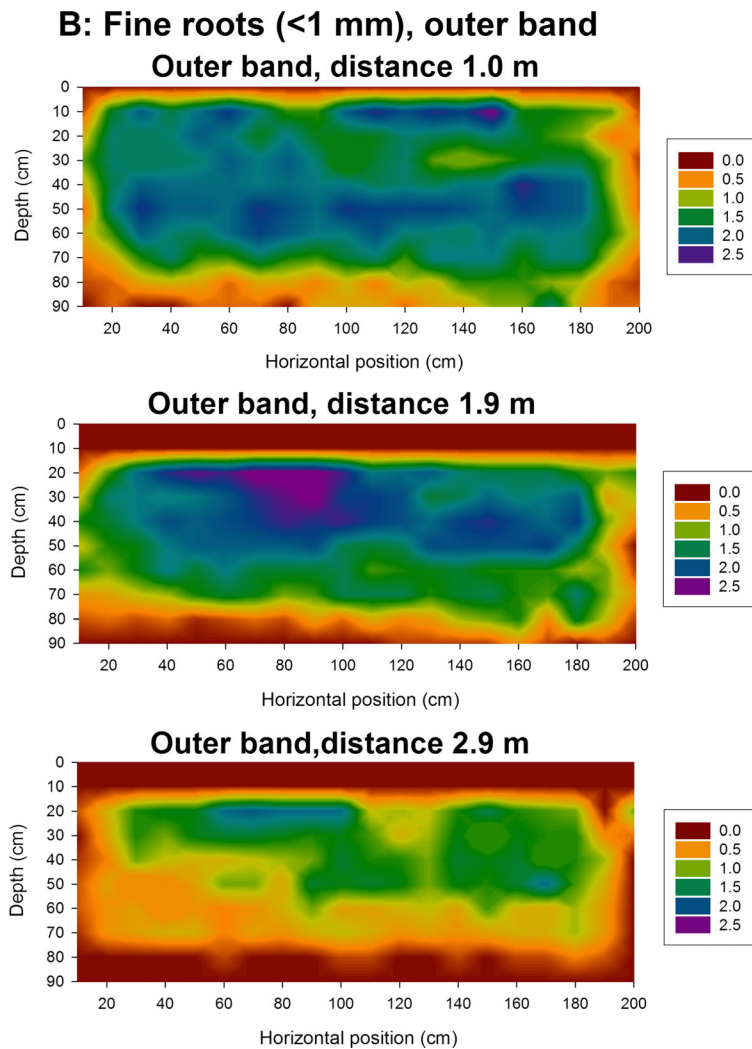
B: Fine roots (<1 mm), outer band

Outer band, distance 1.0 m

Outer band, distance 1.9 m

Outer band, distance 2.9 m

Fig. 6 (continued)

dividing them after species, age classes (e.g. seedlings, young stands and stands) and growing conditions (plants in pots, nursery plants and plants in greenhouses) wherever possible. In this study, average data for the threshold values provided by van den Burg (1985 and 1990) have been used, suggesting nutrient deficiencies of K and Mn. Even though the concentration of these nutrients was low in the foliage, no visual observations of deficiency symptoms on the leaves were observed, presumably because the deficiencies have not, at this stage, been severe enough to induce visible symptoms. However, this could also indicate that diagnostic values of nutrient concentration in the foliage of urban trees may require further studies.

In this study, data from soil analysis of nutrient concentrations were compared to similar intervals, recommended in Danish literature based on agricultural research. This was only done to interpret the magnitude of the nutrient concentration in the soil. The relative high pH level in the soil decreases the plant availability of especially Mn and Fe. In general, the chemical analyses of both soil and foliage suggested that well-constructed structural soil can support tree growth for more than a decade, as the trees at the study site were supplied with sufficient nutrients up till the time of felling. However, deficiencies of K and Mn were detected from foliar analyses and at the same time the concentration of these nutrients in the soil were relatively low. Hence, decreasing uptake of these nutrients may

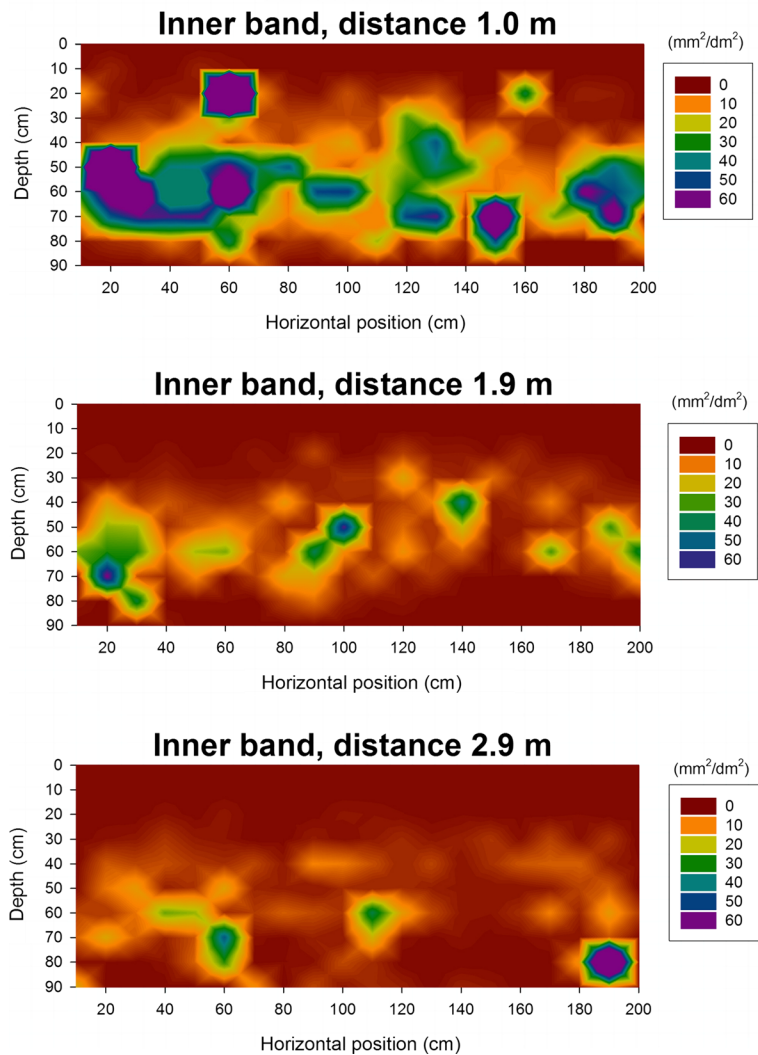## A: Coarse roots (>1 mm), inner band

Fig. 7 Contour plots of the distribution of coarse roots for the inner band (a) and the outer band (b) of trees. The vertical position is measured from the upper edge of the paving, horizontal position is measured from the edges of the structural soil layer, where 0 is pointing towards the middle of the elliptical bands

have impaired future vital tree growth if the trees had continued to grow at the square of Kongens Nytorv.

The difference in construction of the structural soil between the inner and outer band probably contributed to more favourable chemical properties of the soil in the inner band. The differences mainly occurred at depths below 50 cm, and at the greatest distances from trees, i.e. where the construction differences were most pronounced. Foliar analysis indicated that the construction error was not reflected in differences in the nutrient status of the trees in the different bands. Hence, even though the construction error had decreased the nutrient

concentration in the soil significantly and lead to decreased tree growth, a lowered foliage nutrient status could not be observed.

Concentrations of nutrients in the soil were only affected by the distance to trees for C, N and Ca. The concentration of these nutrients was lowest closest to the trees, indicating that the turnover of organic matter and nutrient uptake might be influenced by the proximity to trees. The C/N-ratio was generally higher in the outer band compared to the inner band, often above 25 in depths below 50 cm, indicating potentially slower mineralisation of the organic matter.

B: Coarse roots (>1 mm), outer band

Outer band, distance 1.0 m

Outer band, distance 1.9 m
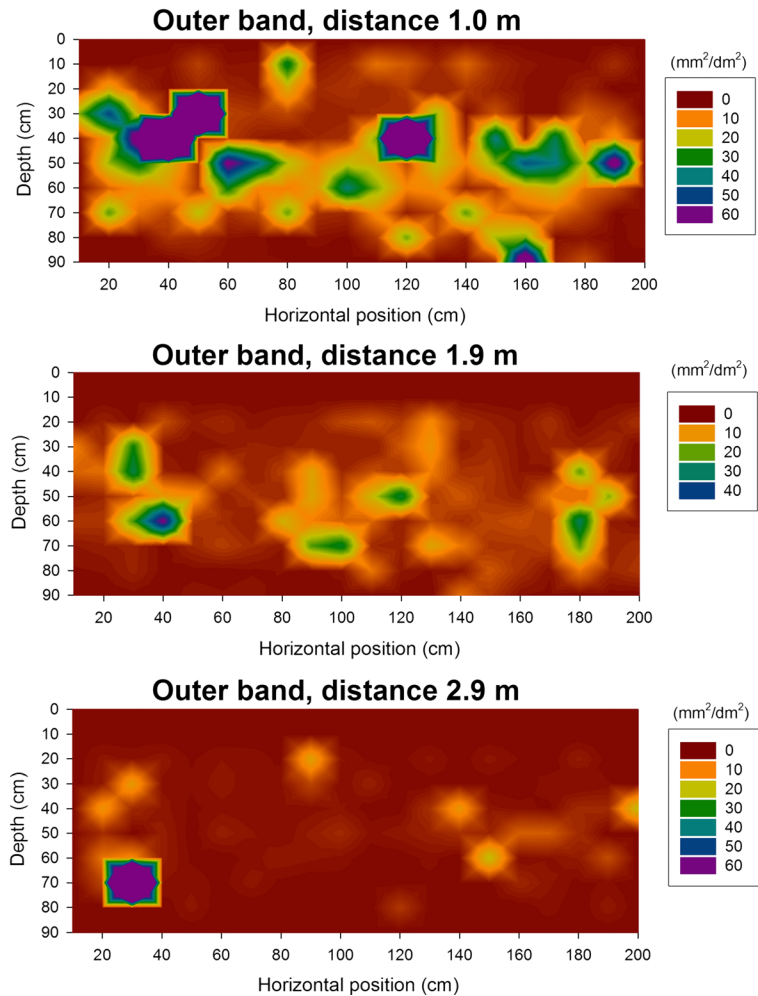
Outer band, distance 2.9 m

Fig. 7 (continued)

Regarding nutrient deficiencies, the Mn deficiency appeared to be the most severe problem, judged by the foliar analysis. However, this could be mitigated by applying a combination of Mn fertilizer and soil acidification by ammonium thiosulfate ($(NH_4)_2S_2O_3$), either by injection in the soil or through the irrigation pipe. Research within agriculture shows this to be effective without causing adverse effects on soil chemistry (Husted et al. 2005). In future urban plantings, we suggest using soil mixtures originating from regions where soil pH and concentration of Ca is lower compared to what was used at the given experimental site.

In Copenhagen, *Tilia* sp. is a common street tree accounting for 29 % of street trees established between 1990 and 2000. Mean annual ring width reported from

earlier studies for these trees is 4.25 mm ($n = 632$) (Bühler et al. 2007). In comparison, the mean annual ring width for the 10 selected trees in this study was 4.15 mm, i.e. quite close to the average for *Tilia* sp. reported by Bühler et al. (2007). The trees in the inner band performed above average with a mean annual ring width of 4.75 mm. However, compared with trees of the same genus growing in a rural environment in undisturbed soil conditions outside Copenhagen (at the Urban Tree Arboretum, Hørsholm), mean annual ring width of the urban trees is approx. 40 % lower (Bühler et al. 2007; Bühler and Kristoffersen 2009) .

As the analysis of annual ring width showed no systematic differences between trees in either band before transplantation, there was no indication of

Table 5 Leaf weight ($n = 100$) and concentration of nutrients in the leaves

	Mean	Min.	Max.
Leaf weight [g/leaf]	0.383	0.216	0.803
Concentration			
C [mg/g]	476	469	485
N [mg/g]	19.6	18.0	21.8
P [mg/g]	2.10	1.40	3.76
K [mg/g]	5.59	4.50	9.12
Ca [mg/g]	23.0	17.3	27.6
Mg [mg/g]	2.86	2.31	3.76
Fe [µg/g]	310	241	473
Mn [µg/g]	13.8	11.1	17.2
Na [µg/g]	123.0	85.6	165.8
Zn [µg/g]	16.8	11.2	21.4
S [mg/g]	1.36	1.24	1.54

differences in terms of nursery plant quality. Since no significant differences of stem growth between inner and outer band can be found for the entire planting, a confined influence specifically related to the 10 investigated trees must have caused the differences in growth measured. Presumably, these differences can be attributed to differences in construction of the structural soils. The soil in the outer band was poorer compared to the inner band, due to a higher content of coarse sand caused by the construction error. However, this difference was relatively small and the effect of texture differences alone on tree growth must be considered of minor importance. The observed differences in tree growth between the bands were assumedly caused by differences in soil structure, i.e. the compacted layer in the outer band. This is supported by root measurements, showing limited root growth in the erroneously compacted layer in the outer band. In addition, the erroneously compacted layer may have acted as barrier for root extension through and below this layer. That soil compaction can decrease tree growth is, e.g., mentioned by Kozlowski (1999). In conclusion, the erroneously constructed part of the outer band highlights the importance of precise descriptions of construction procedures supported by inspection or control routines.

Bartens et al. (2010) suggest that trees grown in structural soils achieve higher stability than trees established by conventional methods. Root deformations, as seen in profile excavations, reveal that coarse root morphology is in fact influenced by the stone matrix. At the study time, no apparent effects on the paving could be observed. Further studies are needed to provide information on the long-term effects of the interaction between roots and infrastructure.

Based on the results of this study, it seems that the volume and particularly the depth of structural soil layers could be increased with beneficial effects for root growth. Oxygen poor conditions and soil compaction were only observed in isolated cases caused by incorrect (re-)construction of the structural soil, which together with the presence of roots in the entire depth of the profile, indicates that roots would be able to exploit deeper layers of soil than the depth (60 cm) provided at the square of Kongens Nytorv. Facilitation of growth in deeper pits would not only increase water and nutrient supply, but also reduce potential negative impacts on surface structures from root growth. We suggest to increase the depth of structural soil layers (e.g. to 90 cm), provided that natural or artificial drainage can be ensured or supported by installation of aeration.

Decaying remnants of deceased *Ulmus* sp. roots were observed at the edges of the excavated profiles. Roots of *Tilia* in this study were observed to grow in the immediate vicinity and also through the decomposing Elm roots. Presumably, the decomposing roots contributed to favourable rooting conditions for the root growth of the *Tilia* trees. Although no research on this matter is available for structural soil systems, it has been documented for other crop systems that decomposing roots and old root channels create improved conditions for root proliferation in regard to nutrient supply, reduced soil strength, aeration and soil moisture (Köstler et al. 1968, McKee 2001, Sucre and Fox 2009) This might be particularly beneficial for trees growing in urban environments, characterized by small soil volumes of questionable quality. Earlier studies by the municipality of Copenhagen also suggest that trees planted at locations previously occupied by Elm trees had a significantly larger stem diameter increment than trees planted at sites without Elms (Bühler et al. 2007).

Root measurements showed that even 10 years after establishment, the bulk of coarse and fine roots were located within the first 2 m from the trunk. This stresses the importance of accessible soil volumes in the immediate proximity of the trunk in particular in

the early life stages of the tree and should encourage landscape architects and urban tree officers to, wherever possible, design round or quadratic structural soil volumes instead of the often seen narrow bands to increase root growth possibilities. A planting pit design allowing the root system to spread in all directions would supposedly also contribute to greater tree stability.

Conclusions

Based on the presented results it can be concluded that structural soils provide a suitable medium for root extension, both horizontally and vertically.

However, by revealing differences in tree root distribution in correctly and erroneously constructed structural soil layers, this study also highlights the importance of accurately describing construction and control procedures in order to achieve sustainable results when implementing the structural soil method for urban trees. Similarly, for excavation and repair work where structural soil is disturbed, accurately described construction procedures are needed to secure correct reconstruction of the structural soil.

Returning to the hypotheses of the study, the investigation at the square of Kongens Nytorv concerning the planting of *Tilia* x *europaea* L. 'Pallida' established that structural soils do support growth of roots in load bearing structures. Furthermore, results showed that these conditions did in fact provide the basis for satisfactory and vital growth of the trees. Thus, hypothesis 1 and 2 could be accepted. Regarding the influence of tree proximity on the concentration of nutrients in the soil, results were inconclusive, as concentration was only affected for C, N and Ca. Hence, hypothesis 3 could only be accepted in part. Hypothesis 4 could be rejected, as nutrient deficiencies were observed in foliar analyses for K and Mn. However, the fact that no visual symptoms were obvious highlights a need for further studies of nutrient concentrations threshold values in urban vegetation.

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