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Root Growth Response of *Platanus orientalis* to Porous Pavements

Justin Morgenroth

Abstract. An experiment was established to determine the effect of porous pavement on underlying root growth. An augmented factorial arrangement of pavement profile designs and pavement types was installed and fifty *Platanus orientalis* seedlings were evenly distributed to control plots or one of four treatments. Treated plots were characterized by either porous or impervious pavement pads measuring 2.3 m × 2.3 m, and underlain by either fine sandy loam or a gravel base and compacted subgrade, reflecting two pavement profile designs. Following two growing seasons, root abundance was categorized by diameter and depth. Results suggest root abundance is greater, especially at shallow soil depths, under pavements. Pavements designed with a compacted subgrade and gravel base only exacerbated shallow root growth, though they could decrease total root abundance. Finally, porous and impervious pavements affected root abundance and distribution in similar ways, dismissing the use of porous pavements to promote deeper rooting.

Key Words. Abundance; Biomass; Diameter; Distribution; Oriental Plan; Permeable; Pervious; Road; Sidewalk; Soil Compaction; Street Tree.

The root systems of different tree species have varying architecture, and though some species have a deep tap root that penetrates vertically into the soil, root systems are typically shallow and widespreading. It is generally accepted that most roots grow in the upper 30 cm of soil, and that they spread well beyond the crown (Gilman 1990). This architecture ensures stability and optimal access to water and minerals (Perry 1982). Unfortunately, in urban environments, shallow root growth conflicts with overlying pavements (Kopinga 1994; Nicoll and Armstrong 1998). As roots expand radially, they deform the soil above them, placing tensile stress on the upper surface of overlying pavements (Nicoll and Coutts 1997). While pavements are strong in compression, they are weak in tension, as a result, underlying root growth leads to eventual pavement failure. These conflicts negatively impact both pavements and trees, often necessitating the repair or replacement of both. It's important to recognize that not all pavement damage is due to underlying roots; engineering faults and underlying soil type can result in cracking as well (Sydnor et al. 2000). Standard pavements are designed to be impermeable for structural purposes, but if cracked, can expose underlying soil to atmospheric conditions, such as precipitation and relatively high oxygen concentration. D'Amato et al. (2002) found that significantly greater root growth was located beneath existing cracks, and suggested that increased soil aeration beneath the crack resulted in greater root growth. In what could be considered a positive feedback loop, root growth can cause pavement failure and pavement failure can promote root growth. Unlike structural pavements, some pavements are designed to be permeable to air and water; these are called porous pavements. While it had previously been suggested that porous pavements may be a solution to conflicts with roots (Barker 1988), high permeability may result in improved soil conditions for root growth and hence, increased incidence of conflict. To understand how different pavement types and profile designs affect underlying root growth, this experiment's objective was to contrast root growth in open grown trees with those surrounded by porous and impervious pavements.

METHODS

Study Site and Experimental Design

A comprehensive description of the study site and experimental design was previously described by Morgenroth and Visser (2011), nevertheless, an abbreviated description is provided herein. The experiment was located at the city council nursery on the outskirts of Christchurch, New Zealand (Lat: -43.493, Long: 172.437). Fifty, one-year-old, bare root oriental plane (*Platanus orientalis*) seedlings were randomly assigned to plots in an augmented factorial experiment consisting of controls and four treatments; trees were split evenly among treatments. The treatments were based on the combination of pavement type (2 levels: porous, impervious) and pavement profile design (2 levels: +/- subgrade compaction and gravel base). The resulting four treatments were impervious concrete pavement (IP), impervious concrete pavement with compacted subgrade and gravel base (IP+), porous concrete pavement (PP), and porous concrete pavement with compacted subgrade and gravel base (PP+). The distinction between the two levels of pavement profile design is related to the preparation of the profile below the pavement surface course. The profile design of IP and PP plots was characterized by a concrete pavement surface course installed over leveled topsoil, whereby the profile design of IP+ and PP+ plots included a concrete pavement surface course installed over a leveled gravel base and compacted subgrade. Soil penetration resistance in the uppermost 30 cm of soil in plots, following treatment installation, differed significantly

($P < 0.001$); mean values were 892 kPa, 874 kPa, 808 kPa, 2458 kPa, and 2363 kPa for control, IP, PP, IP+, and PP+, respectively.

Data Collection

Root growth and distribution was quantified by measuring total root biomass, as well as categorizing the abundance of roots by depth and diameter. Following concrete pavement removal in March 2009, a square trench was dug around each tree using an Air-Spade® (Concept Engineering Group, Inc., Verona, PA, U.S.) to expose roots. This technique allowed roots, ranging in size from fine through coarse, to be exposed, counted, and measured (Nadezhdina and Čermák 2003). Trenches measured 20 cm wide × 50 cm deep, and the distance between the tree stem and the nearest point on the inside wall of each trench was 100 cm. Root abundance in the trenches was categorized into three discrete root diameter classes (fine: < 2 mm, medium: 2–5 mm, and coarse: > 5 mm), and six depth classes each comprising a 5 cm deep soil layer. Following collection of abundance data, the excavation tool was used to remove all remaining soil surrounding each tree, allowing excavation of entire root systems. Whole root systems were placed in a kiln and dried at 70°C to constant weight (Nicholson 1984).

The cumulative proportion of roots from the soil surface was calculated for all trees. Following Gale and Grigal (1987), an asymptotic nonlinear model was used to describe vertical root distribution:

$$Y = 1 - \beta^d \quad [1]$$

where Y is the cumulative proportion of roots counted between the soil surface and depth d in centimeters, and β is the estimated parameter. β was used as a relative index of the vertical root distribution across treatments. High values of β are associated with relatively deep root systems, whereas low values indicate proportionally shallow root systems.

Statistical Analysis

One IP+ tree died between the first and second growing seasons and thus was excluded in all analyses. No roots were found below 30 cm soil depth, so analyses were limited to the uppermost 30 cm. Root abundance data were analyzed using a generalized-linear model with a quasi-poisson distribution. Treatment differences were determined via analysis of deviance (Crawley 2007). Estimated β coefficients (Equation 1) and belowground biomass were compared via one-way analysis of variance (ANOVA) using orthogonal, *a priori*, single degree-of-freedom contrasts to examine treatment effects, as well as interactions of interest (Marini 2003). All significant differences are reported for $P < 0.05$. Analyses were performed using the R statistical package, version 2.8.1 (R Development Core Team 2008).

RESULTS

Root Biomass

Belowground biomass depended on treatment ($p = 0.002$). Mean root biomass of control plots did not differ from pavement treated trees, however, there were differences related to pavement type and profile design, as well as their interaction (Table 1). In IP+ and PP+ plots, root biomass was unaffected by pavement type, but in the absence of a compacted subgrade and gravel base, root biomass beneath porous pavements significantly exceeded root biomass beneath impervious pavements (Figure 1).

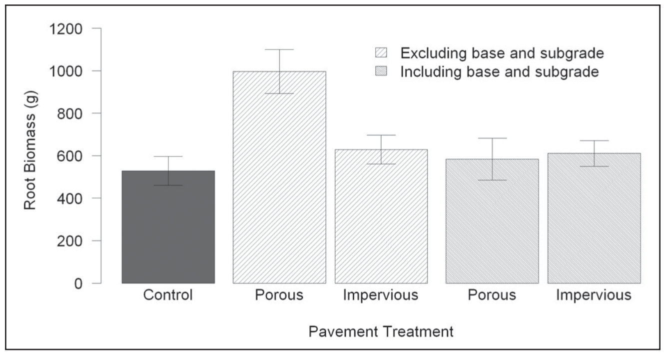

Figure 1. The effect of pavement type and profile design on mean root biomass of *Platanus orientalis*. Error bars represent one standard error.

Vertical Root Distribution

Root allocation was greatest at shallower depths with over 90% of roots, irrespective of treatment, growing in the uppermost 20 cm of soil (Figure 2). The index used to measure vertical root distribution, β, ranged from 0.900 to 0.937 (Figure 2), where higher values signify relatively deeper root distribution (Gale and Grigal 1987). Control plots had comparatively higher β values than paved plots (Table 1, contrast 1), indicating that proportionally more roots grew deeper than in paved plots. Figure 2 illustrates this well; only c. 53% of roots from control trees grew in the uppermost 15 cm of soil, whereas the percentage of roots growing in this same 15 cm soil layer for pavement-treated trees was greater, ranging from c. 75% to 84%.

Changes in pavement profile design also affected vertical root distribution (Table 1, contrast 2); roots grew relatively deeper under pavements without a compacted subgrade and gravel base, thereby resulting in a relatively higher β values for IP and PP plots (Figure 2). Pavement profile design differences were most prevalent in the uppermost 10 cm, where c. 42% of roots grew in IP and PP plots, in contrast to c. 56% of roots from IP+ and PP+ plots (Figure 2). No pavement-type effect existed, implying that vertical root distribution beneath porous and impervious pavements was equivalent, regardless of pavement profile design.

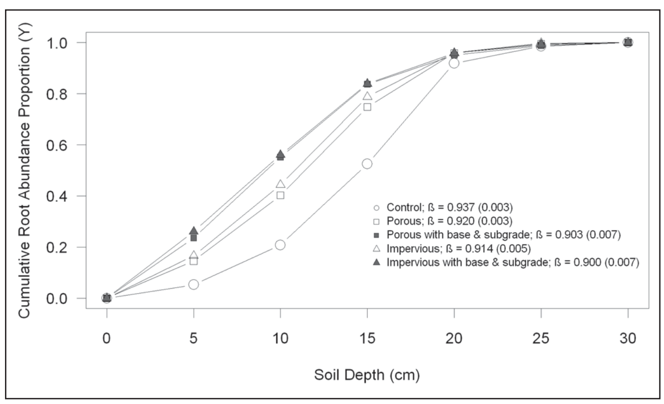

Figure 2. The effect of pavement type and profile design on cumulative root abundance (Y) with increasing soil depth (d). Mean β values (1 s.e.) indicating vertical root distribution were derived from $Y = 1 - \beta^d$.

Table 1. *P*-values for single degree-of-freedom contrasts comparing the effect of pavement type and profile design on root biomass and β, the index used to measure vertical root distribution.

Contrasts	df	$p_{biomass}$	p_{β}
1. Control versus all other treatments	1	0.062	< 0.001*
2. Main effect (pavement profile design)	1	0.013*	0.002*
3. Main effect (pavement type)	1	0.047*	0.243
4. Interaction (pavement profile design x pavement type)	1	0.022*	0.976

* $P < 0.05$.

Root Abundance

A comprehensive understanding of root dynamics was obtained by contrasting treatment effects on the abundance of roots of varying diameters at different soil depths. Some general trends, irrespective of root diameter class, were evident throughout the abundance data. First, within-treatment abundance generally increased in each successive 5 cm soil increment throughout the uppermost 15–20 cm (depending on treatment); below this, root abundance decreased abruptly (Figure 3). Within each class of root diameter size, treatment effects were present only in the top 20 cm of soil. Abundance of roots from 20–30 cm depth was statistically similar across all treatments (Table 2).

In the uppermost 20 cm of soil, all pavement treatments altered root abundance and distribution relative to control plots (Table 2, contrast 1). Vertical root distribution followed a similar pattern in both fine and medium diameter roots. From the soil surface to 10 cm depth, control plots had significantly fewer roots than paved treatments (Table 2, contrast 1). From 10–15 cm depth, root abundance in control plots increased, whereas mean root abundance for paved treatments remained stable. As a consequence, no significant difference was found between controls and paved plots at this depth. Finally, between 15–20 cm depth, a significant difference reemerged; however, this time control plots had a greater abundance of roots than all paved plots.

A truncated version of this pattern existed for coarse roots. No difference existed between controls and paved plots in the uppermost 10 cm, but then between 10–15 cm depth, greater root abundance was exhibited beneath paved plots. The converse was true from 15–20 cm, as root abundance was greater in control plots. Whereas root abundance beneath pavement treatments was greatest between 10–15 cm deep, maximum root abundance in control plots did not typically occur until 20 cm depth (Figure 3). This difference in root distribution was corroborated by β values, which suggested relatively shallow allocation of roots in paved plots and relatively deep allocation in control plots (Figure 2).

The effect of pavement profile design was seen in all three root diameter classes, but only in the layer 10–20 cm beneath the soil surface (Table 2, contrast 2). In each root diameter class, the mean root abundance for IP and PP plots exceeded that for IP+ and PP+ plots. Thus, there were a greater number of fine, medium, and coarse roots in the 10–20 cm soil depth under pavements without a compacted subgrade and gravel base.

Alone, pavement type never affected root abundance (Table 2, contrast 3), implying that mean root abundance was similar beneath porous and impervious pavements. Further inspection revealed an interaction between pavement type and profile design, which affected fine roots 5–15 cm beneath the soil surface (Table 2, contrast 4). Without a compacted subgrade and gravel base, porous pavements yielded significantly greater fine root abundance than impervious pavements. Conversely, when pavement profiles were designed to include a compacted subgrade and gravel base, the abundance of fine roots was greater beneath impervious pavement (Figure 3).

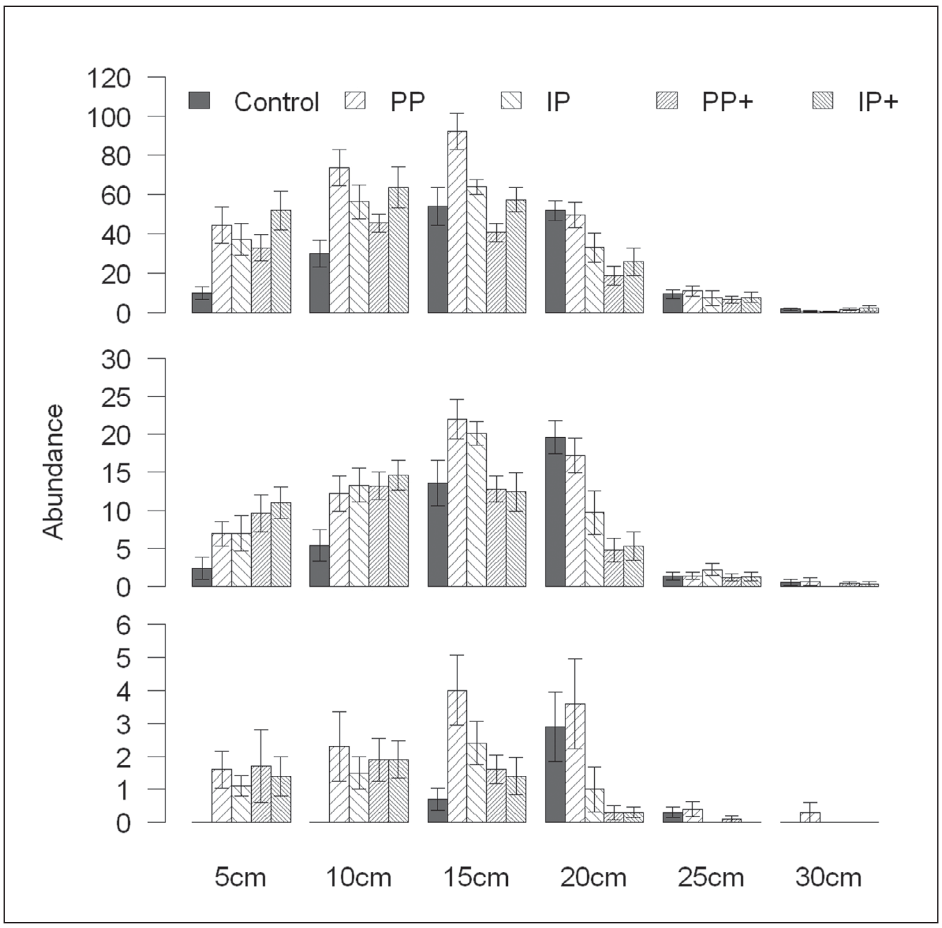

Figure 3. The effect of pavement type and profile design on mean abundance of roots by soil depth. Top: fine roots (< 2 mm); Middle: medium roots (2–5 mm); and Bottom: coarse roots (> 5 mm). Note: the scale of the y-axis differs between plots.

Table 2. *P*-values for single degree-of-freedom contrasts comparing the effect of pavement type and profile design on root abundance within root diameter and soil depth classes.

	Soil depth (cm)																	
	0-5			5-10			10-15			15-20			20-25			25-30		
	Root diameter (mm)																	
Contrast	<2	2-5	>5	<2	2-5	>5	<2	2-5	>5	<2	2-5	>5	<2	2-5	>5	<2	2-5	>5
1. Control versus all other treatments	0.001	0.020	0.995	0.003	0.004	0.994	0.388	0.326	0.046	0.005	<0.001	0.013	0.621	0.895	0.994	0.325	0.995	0.999
2. Main effect (pavement profile design)	0.924	0.155	0.722	0.232	0.632	0.946	<0.001	0.002	0.024	0.006	0.001	0.025	0.475	0.367	1.0	0.084	0.995	0.999
3. Main effect (pavement type)	0.475	0.782	0.503	0.813	0.602	0.523	0.922	0.691	0.305	0.844	0.381	0.426	0.713	0.480	0.994	0.868	0.995	0.999
4. Interaction (pavement profile design × pavement type)	0.117	0.823	0.831	0.046	0.968	0.523	0.005	0.849	0.546	0.086	0.216	0.426	0.404	0.621	1.0	0.568	0.995	0.999

DISCUSSION

The results support the hypothesis that root biomass differs beneath porous and impervious pavements but only in the absence of a compacted subgrade and gravel base (Figure 1). Given that coarse roots contribute more to total root biomass than fine or medium fractions (Misra et al. 1998), it was believed that treatment differences would also arise in coarse root abundance. Within individual depth classes, this was rarely true, possibly due to low overall frequencies and high within-treatment variation (Figure 3). Nevertheless, a closer look was warranted, given the propensity for coarse roots to contribute to conflicts with pavements (Nicoll and Armstrong 1998). Further inspection revealed that coarse root abundance, like root biomass, increased beneath porous pavement, but only in plots without a compacted subgrade and gravel base. The mean number of coarse roots found beneath PP treatments was 12.2, compared with only 6 for IP treatments. Mean values for control (3.9), PP+ (5.6), and IP+ (5) treatments were all comparable to IP. Of particular interest, data revealed that in the uppermost 10 cm of soil in control plots, no coarse roots were present, while paved plots had mean abundances ranging from 2.6–3.9 coarse roots per plot depending on treatment. This is noteworthy because coarse roots at shallow depths have the potential to conflict with overlying pavements by deforming adjacent soil during radial growth (Nicoll and Armstrong 1998). It's likely that deeper root distribution for control plots is a response to diurnal temperature variation (Hillel 1998) and fluctuating moisture (Morgenroth and Buchan 2009) which readily occur at shallow depths. In contrast, coarse roots did grow in shallow soil beneath pavements, where temperature and soil moisture were presumably more stable. Though high within-treatment variation compromised the statistical significance of the analysis, it is reasonable to suggest that coarse root abundance and biomass indicate the potential for pavements and, more specifically, porous pavements without a compacted subgrade and gravel base to result in more, larger roots with the propensity to conflict with overlying pavements.

With greater than 90% of roots in the uppermost 20 cm of soil (Figure 2), the root systems studied in this experiment were consistent with other root systems (Gilman 1990). It was in this 20 cm soil layer that all treatment-related differences in root abundance existed. Results showed that root abundance was greatest in control plots at 20 cm, whereas maximum values were reached in paved plots between 10–15 cm. This difference is likely, indirectly or directly, in response to available soil moisture. As part of a larger experiment, Morgenroth and Buchan (2009) monitored soil moisture for all treatments in this experiment; they showed that, in control plots, soil moisture increased with depth. Root branching and growth are known to increase under optimal soil moisture conditions (Ruark et al. 1983), presumably to take full advantage of the water resource, but also because soil strength is reduced at greater soil moisture, precluding physical obstructions to root growth. Thus, it's likely that the uppermost soil layer in control plots, which was highly prone to moisture fluctuations and likely prone to temperature variation (Hillel 1998), dissuaded root growth, while the deeper layers with more stable soil moisture and temperature promoted root growth.

In contrast to control plots, vertical root distribution beneath pavements was concentrated higher in the soil profile. Much as it did in control plots, high soil moisture may have promoted root growth in paved plots, beginning at shallower levels. This is because in paved plots, there was no dry zone, instead high soil moisture was found directly beneath pavements and extended deep into the soil profile (Morgenroth and Buchan 2009). Another explanation for shallow root growth beneath pavements also pertains to soil moisture, but in an indirect manner. The high soil moisture beneath pavements may have acted as a barrier to oxygen diffusion, leading to the relatively anaerobic conditions found deeper in the soil profile (Morgenroth and Buchan 2009). Since one response of roots to anaerobic soils is to remain near the soil surface (Dittert et al. 2006), it's possible that shallow root growth in this experiment was in response to anaerobic conditions present in the deeper soil layers beneath paved surfaces. Tree species with different tolerances to soil anaerobiosis would certainly have differed in their response as has been seen in other studies (Day et al. 2000).

Root abundance and distribution were also affected by pavement profile design. Trees exhibited relatively shallow root growth in paved plots designed with a compacted subgrade and gravel base (Figure 2). Differences in root abundance were significant between 10–20 cm, where abundance was greater in IP and PP plots (Table 2, contrast 2). To explain these differences, we must consider how pavement profile design affected soil physical conditions, in particular, soil compaction.

The rooting environment for trees in IP+ and PP+ plots included a compacted subgrade with mean soil strength of 2411 kPa. Since soil strengths of between 2000–3000 kPa are known to limit root growth (Sinnett et al. 2008), the compacted subgrade in IP+ and PP+ plots may account for lower observed mean root abundance. Another effect of compaction is reducing soil aeration; this is because macropores are lost in favor of micropores, which are preferentially filled by water rather than air. As previously explained, low soil aeration can cause shallow root growth, which may explain the relatively lower β values, and hence shallower root distribution, for IP+ and PP+ plots.

From the perspective of tree growth, pavement profile designs without a compacted subgrade and gravel base are preferable as these resulted in greater root abundance from 10–20 cm soil depth. Porous pavements were even more advantageous than impervious pavements given this profile design as they resulted in greater root biomass, as well as enhanced aboveground growth (Morgenroth and Visser 2011). From the perspective of minimizing conflicts between roots and pavements, the effect of porous and impervious pavements were similar; however, pavement profile designs that include a gravel base are preferable to those without. This is because, in this experiment, the inclusion of a compacted subgrade and gravel base resulted in fewer roots and, while those roots were significantly shallower within the soil profile, the gravel base ensured that they were never nearer than 20 cm from the underside of the pavement.

CONCLUSION

It is understood that although root architecture is under genetic control, the soil environment in which trees grow can influence root growth and distribution (Pritchett 1979). In this experiment, the soil environment was overlaid by pavement treatments. Previous research has shown that pavements can significantly impact a soil's physical characteristics such as soil moisture and aeration (Morgenroth and Buchan 2009), and temperature (Graves 1994; Wagar and Franklin 1994). These impacts offer a plausible explanation to the measured treatment effects, including greater root abundance and shallow root distribution in paved relative to unpaved plots; decreased root abundance below IP+ and PP+ plots relative to IP and PP plots; and greater root biomass beneath porous pavements relative to impervious pavements in the absence of a compacted subgrade and gravel base. Future studies should test the effect of these treatments on different tree species grown in various soil types and climates to validate and generalize these results.

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Résumé. Une expérience a été mise au point pour déterminer l'effet d'une surface pavée poreuse par rapport à la croissance des racines endessous. Différents types de pavage ainsi qu'une variation accrue dans la conception du profil de chacun des types de pavages ont été installés et cinquante semis de Platanus orientalis ont été par la suite distribués de manière égale parmi l'unité témoin ainsi qu'entre les quatre types d'unité à tester. Les unités à tester étaient caractérisées soit par une surface pavé poreuse ou soit par une surface imperméable mesurant 2,3 × 2,3 m et avec une fondation sous-jacente composée soit d'un loam sablonneux fin ou de pierre concassée posée sur une sous-fondation compacté, ce qui représentait deux types différents de design de profil. Après deux saisons de croissance, l'abondance en racines a été caractérisée en fonction de leur diamètre et de leur profondeur. Les résultats montrent que l'abondance en racines est plus grande, plus spécialement à faible profondeur dans le sol, sous le pavage. Les surfaces pavées conçues avec sous-fondation compactée et une fondation en pierre concassée fine ne font qu'exacerber la croissance des racines à faible profondeur, et ce même si cela entraîne un déclin de l'abondance générale en racines. Enfin, les surfaces pavées poreuses et imperméables ont affecté l'abondance en racines et leur distribution de manière similaire, ce qui décourage l'intérêt de faire appel aux surfaces pavées poreuses pour promouvoir un enracinement plus profond.

Zusammenfassung. Es wurde ein Experiment aufgebaut, um die Auswirkungen von poröser Pflasterung auf die darunter wachsenden Wurzeln zu bestimmen. Dazu wurden vergrößerte Arrangements von verschiedenen Pflasterprofilen installiert und darin 50 Platanen-Sämlinge (Platanus orientalis) gleichmäßig in der Kontrollfläche oder in einer von vier Versuchsflächen verteilt. Die Versuchsflächen waren gekennzeichnet durch entweder poröse oder undurchlässige Bodenbeläge in der Ausdehnung von 2,3 m x 2,3 m, deren Unterbau entweder aus sandigem Lehm oder Schotterbasis und verdichtetem Untergrund bestand, welches zwei typische Pflasterprofile kennzeichnet. Nach zwei Wachstumsperioden wurde die Wurzelentwicklung anhand von Durchmesser und Tiefe kategorisiert. Die Ergebnisse zeigten, dass die Wurzelentwicklung besonders bei flachen Bodentiefen unter dem Pflaster größer ist. Plasterungen mit einem kompakten Untergrund und einer Schotterbasis erlaubten nur ein flaches Wurzelwachstum, daher können sie die totale Wurzelausdehnung begrenzen. Schließlich beeinflussten poröse und undurchlässige Pflasterungen die Wurzelausdehnung und –Verbreitung in ähnlicher Weise, was die Verwendung von porösen Pflasterungen zur Begünstigung von tieferem Wurzeln von der Hand weist.

Resumen. Se estableció un experimento para determinar el efecto del pavimento poroso en el crecimiento de las raíces. Se instaló un arreglo factorial de diseños de perfiles y tipos de pavimentos y se distribuyeron 50 brinzales de Platanus orientalis en parcelas de control, o uno de cuatro tratamientos. Las parcelas tratadas fueron caracterizadas por contar con pavimento poroso o impermeable de 2.3 m × 2.3 m, y con fondo franco arenoso o grava y subsuelo compactado, reflejando dos diseños de perfiles de pavimentos. Después de dos estaciones de crecimiento se categorizó la abundancia de raíces por diámetro y profundidad. Los resultados sugieren que la abundancia de raíces es mayor, especialmente en suelos poco profundos, bajo pavimentos. Los pavimentos diseñados con subsuelo compactado y grava solamente exacerbaron el crecimiento de las raíces superficiales, a pesar de que ellas pudieron haber disminuido en abundancia. Finalmente, los pavimentos porosos e impermeables afectaron la abundancia de raíces y su distribución en formas similares, sugeriendo el uso de pavimentos porosos para promover raíces profundas.