Urban Forestry & Urban Greening 33 (2018) 27–36

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Porous-permeable pavements promote growth and establishment and modify root depth distribution of *Platanus* × *acerifolia* (Aiton) Willd. in simulated urban tree pits

Francisco Javier de la Mota Daniel[a,*], Susan D. Day[a,b], James S. Owen Jr.[c], Ryan D. Stewart[d], Meredith K. Steele[d], Venkataramana Sridhar[e]

[a] Department of Horticulture (0327), Virginia Tech, Saunders Hall, 490 West Campus Dr., Blacksburg, VA 24061, United States
[b] Department of Forest Resources and Environmental Conservation (0324), Virginia Tech, Cheatham Hall, 310 West Campus Dr., Blacksburg, VA 24061, United States
[c] Department of Horticulture, Virginia Tech, Hampton Roads Agricultural Research and Extension Center, 1444 Diamond Springs Rd., Virginia Beach, VA 23455, United States
[d] Department of Crop and Soil Environmental Sciences (0404), Virginia Tech, Smyth Hall, 185 Ag Quad Lane, Blacksburg, VA 24061, United States
[e] Department of Biological Systems Engineering (0303), Virginia Tech, Seitz Hall, 155 Ag Quad Lane, Blacksburg, VA 24061, United States

ARTICLE INFO

Keywords:
London plane
Pervious pavement
Resin-bound gravel
Soil temperature
Street tree
SuDS

ABSTRACT

In dense urban areas with heavy pedestrian traffic, current trends favor covering tree pits with porous-permeable pavement over installing grates or leaving the soil exposed. However, pavement cover potentially modifies soil moisture and temperature, altering tree growth and overall resilience, especially when coupled with heat stress and drought in a changing climate. This study evaluated the response of newly planted London plane (*Platanus* × *acerifolia* 'Bloodgood') trees to porous-permeable resin-bound gravel pavement and associated alterations in soil water distribution and temperature, in two distinct physiographic regions in Virginia, USA. Simulated urban tree pits were either covered with porous-permeable pavement or left unpaved, and root growth and depth, soil water content and temperature, and tree stem diameter measured over two growing seasons. At both sites, trees in paved tree pits grew larger than trees without pavement. Stem diameters were 29% greater at the Mountain site and 51% greater at the Coastal Plain site, as were tree heights (19% and 38% greater), and above ground dry biomass (67% and 185% greater). Roots under pavement developed faster and shallower, with many visible surface roots. In contrast, unpaved tree pits had almost no visible surface roots, and at the Mountain site only occupied an average area of 7 cm^2 within the 1-m^2 tree pits, compared with 366 cm^2 in paved tree pits. Pavement may have extended the root growing season by as much as 14 days, as the average soil temperature for the month of October was 1.1 °C and 1.2 °C higher under pavement than in unpaved pits. Porous-permeable pavement installations in tree pits accelerated establishment and increased growth of transplanted trees, but may result in shallower root systems that can damage pavement and other infrastructure. In addition, shallow root systems may prevent water extraction from deeper soils, compromising drought resilience.

1. Introduction

Urban trees provide ecosystem services including environmental cooling, stormwater runoff reduction, and enhanced emotional well-being (Mullaney et al., 2015b; Livesley et al., 2016). Yet in densely built environments, such as urban centers, trees in streets and plazas are typically growing in pavement cutouts (usually known as tree pits), which are known to pose significant challenges for tree growth (Grabosky and Gilman, 2004; Day and Amateis, 2011; Sanders et al., 2013) and survival (Lu et al., 2010), and thus curtail ecosystem service provision. Tree pits may, however, provide the only greenspace in an otherwise surface-sealed environment that limits rainfall infiltration into the soil (Scalenghe and Marsan, 2009). Consequently, cities are exploring the potential of utilizing these pavement cutouts and resident urban trees to improve stormwater management efforts (Fitzgerald and Laufer, 2017). As part of these efforts, permeable pavements are considered a sustainable drainage system (SuDS) that can reduce stormwater runoff up to 70% (Rodríguez-Rojas et al., 2018). Stormwater mitigation is also an important function of urban forests (McPherson et al., 2005; Berland et al., 2017); thus designing tree pits that support tree growth and allow for enhanced water infiltration can provide synergistic benefits. Furthermore, improved tree pit design that provides

* Corresponding author.
E-mail address: delamota@vt.edu (F.J. de la Mota Daniel).

https://doi.org/10.1016/j.ufug.2018.05.003
Received 1 February 2018; Received in revised form 1 May 2018; Accepted 8 May 2018
1618-8667/ © 2018 Elsevier GmbH. All rights reserved.

a more desirable rooting environment could complement recent efforts on tree species selection for climate adaptation (McPherson et al., 2018).

Common tree pit coverings include tree grates and different types of permeable pavement. Terms for describing various types of permeable pavement are varied. We will use pavers to describe any of various types of nonporous-permeable installations such as cobblestones or bricks, and porous to refer to porous-permeable materials such as flexible pavements and resin-bound gravel products that typically provide continuous coverage (i.e., their permeability arises from the material itself). Porous materials have gained rapid popularity, often replacing bare soil, grates, mulches or traditional pavements. Permeable pavements are often employed to facilitate stormwater infiltration and enhance tree growth and survival (Mullaney et al., 2015b), while providing a level and continuous surface for pedestrian use. Savi et al. (2015), however, found increased drought stress in *Quercus ilex* L. under impermeable pavement, raising concerns about resilience of pavement-covered rooting zones under climate change. In general, pavements are linked to premature decline and death of trees (Kjelgren and Clark, 1994; Iakovoglou et al., 2001; Schröder, 2008), presumably because physical or chemical impediments restrict root systems (Day et al., 2010b). Tree roots may grow preferentially in the upper soil layers (Crow, 2005; Wang et al., 2006) regardless of soil cover. However, interactions among soil compaction, texture, soil moisture and tree species also affect rooting depth (Day et al., 2010a). Thus, pavements and pavement type likely influence root growth and plant response by altering soil temperature, water content, or other soil properties.

Permeable pavements store less heat than impermeable ones (Kevern et al., 2012), but heat up faster and to a greater extent (Kevern et al., 2009). Very high soil temperatures impede or halt root growth (Kaspar and Bland, 1992; Harris et al., 1995). Asphalt, presumably because of its dark color, may raise soil temperature to above 40 °C (Celestian and Martin, 2004), while for most temperate tree species favorable root growth temperatures are under 30 °C (Graves, 1994).

Studies on the effect of permeable pavement on soil moisture and temperature, and consequently, on trees, are often contradictory and specific to each site. In New Zealand, soil moisture was higher directly under pavements (both permeable and impermeable) in a sandy loam due to distillation caused by pavement cooling, and reduced evaporation (Morgenroth and Buchan, 2009; Morgenroth et al., 2013). This, in turn, promoted shallower root development (Morgenroth, 2011) and greater tree growth (Morgenroth and Visser, 2011) of *Platanus orientalis* L., presumably reducing differences in soil water content between pavement and bare soil over time (Morgenroth and Buchan, 2009). This increased soil moisture under pavement was not as pronounced when a gravel base course was installed under the pavement (Morgenroth et al., 2013). Similar results were found in an Australian study for clay soils, while a gravel base course increased soil water content near the surface in sandy soils (Mullaney et al., 2015a). In this same study, above-ground growth of *Melaleuca quinquenervia* (Cav.) S.T. Blake was increased with pavement only in the presence of a gravel base over clay soil, and only without the gravel base for sandy soil. This suggests that the more optimal (no waterlogging, no drying out) moisture patterns provided by these two pavement profile designs (base layer in clay, and no base layer in sandy soil) promoted tree growth. Thus the physical characteristics and arrangement of soil and gravel layers beneath pavements influence water relations and root growth.

In some cases, installation practices may explain tree response to pavements. For example, pavers with a gravel base course and irrigation reduced the annual stem diameter increment rate of *Pyrus calleryana* Decne. compared with mulched tree pits with no irrigation (Rahman et al., 2013), possibly due to soil compaction for paver installation. Tree life stage can also play a role. In Texas, Volder et al. (2009) did not observe significant differences in moisture and temperature in a clay soil at 5–25 cm deep under various surface treatments including permeable concrete, impermeable concrete (both without a gravel base), and bare soil, over two years. There were also no differences in growth rate, leaf water potential or leaf gas exchange among American sweetgum trees (*Liquidambar styraciflua* L.) planted under similar conditions. The lack of surface treatment effects on soil moisture and temperature was likely because trees were mature and established. Root systems had fully explored the soil area under the pavement and thus water extraction by roots may have dominated the soil moisture regime. Soil temperature may, in turn, have been moderated by the shade of the canopy. Nonetheless, when no base material was installed, both permeable and impermeable pavements reduced root length production and root lifespan of trees (Volder et al., 2014). In contrast, Morgenroth (2011) found that *Platanus orientalis* L. produced more root biomass over two growing seasons under porous pavement without a compacted subgrade or gravel base than under impermeable pavement. In treatments that included a gravel base and compacted subgrade, however, both soil water content and root biomass were comparable to trees in bare soil (Morgenroth, 2011), suggesting again that both soil physical characteristics and the gravel base influence vertical water distribution and thus root growth. Fini et al. (2017) also found greater soil moisture under permeable and impermeable pavement at 20-cm depth compared with bare soil, but it did not lead to increased above-ground growth of *Celtis australis* L. and *Fraxinus ornus* L. trees. Instead, impermeable asphalt reduced transpiration in *Fraxinus ornus* compared with bare soil, pavers, and porous pavement treatments, perhaps due to increased soil temperature under the pavement. Impermeable asphalt was the only treatment in this study where soil temperature exceeded 30 °C, although researchers could not confirm that roots had penetrated below the pavement. In this study there were soil temperature differences among impermeable, permeable and bare soil treatments, but differences were small between porous pavement and bare soil, likely due to similarities in albedo. These various disruptions to soil water movement and temperature by permeable and impermeable pavements may influence soil-plant-water relations, and alter the behavior of tree pit systems, affecting root distribution, tree growth and establishment, all of which have implications for drought resilience and ecosystem service provision.

Explanations for these variable results generally focus on the interaction of factors such as site soils, construction techniques, pavement section design, and climate, which are likely to affect soil physical properties, water content, and temperature. Since ecosystem services provided by urban trees increase in proportion to their size (McPherson et al., 1994; Mullaney et al., 2015b), understanding the response of trees to porous pavement is relevant to maximize such benefits. Thus we created simulated sidewalk cutouts (tree pits) with and without porous pavement planted with London plane (*Platanus* × *acerifolia* (Aiton) Willd. 'Bloodgood') in two different physiographic regions, and monitored below-ground conditions and tree response over the course of two years. Our objectives for this study were to (1) evaluate the influence of porous pavement on tree growth and development during establishment; (2) to assess the role of porous pavement in altering the depth and emergence of roots of establishing trees; and (3) to distinguish above- and below-ground responses to porous pavements mediated by soil water content and temperature.

2. Materials & methods

Each experimental site consisted of 12 simulated tree pits planted with *Platanus* × *acerifolia* 'Bloodgood' trees, which were covered with porous pavement or left without any soil cover.

2.1. Experimental sites

Two sites were selected with differing climates and soils: the Urban Horticulture Center in Blacksburg, VA, USA (Lat. 37.218739, Long. 80.463679, Elev. 622 m); and the Hampton Roads Agricultural

Research and Extension Center in Virginia Beach, VA, USA (Lat. 36.893721, Long. 76.177655, Elev. 9 m.). The Blacksburg site (Mountains) is located in the valley and ridge physiographic region of Virginia with a Groseclose-Poplimento soil series complex (fine, mixed, subactive, mesic Ultic Hapludalf). The A horizon was a silt loam (23% sand, 63% silt, and 14% clay), 30 cm deep with a mean bulk density of 1.37 Mg m^{-3} (SE = 0.01). The B horizon was a silty clay (12% sand, 41% silt, and 47% clay) with a mean bulk density of 1.21 Mg m^{-3} (SE = 0.03). The Virginia Beach site (Coastal Plain) is in the coastal plain with a Tetotum loam (fine-loamy, mixed, semiactive, thermic Aquic Hapludults). The A horizon was a sandy loam (63% sand, 29% silt, and 8% clay), 35 cm deep with a mean bulk density of 1.59 Mg m^{-3} (SE = 0.04). A 30-cm thick Bt horizon was a loamy sand (79% sand, 12% silt, and 9% clay) with a mean bulk density of 1.58 Mg m^{-3} (SE = 0.03). The C horizon was a sand (94% sand, 2% silt, and 4% clay) with a mean bulk density of 1.42 Mg m^{-3} (SE = 0.01). Blacksburg has a humid continental climate (Dfb classification by Köppen), with an annual mean temperature of 10.9 °C, and an annual mean precipitation of 1038 mm, while Virginia Beach has a humid subtropical climate (Cfa classification by Köppen), with an annual mean temperature of 15.3 °C, and an annual mean precipitation of 1200 mm.

2.2. Experimental design and installation

Treatments were installed in a completely randomized design as either 1) paved tree pit with porous-permeable resin-bound gravel pavement (PP) or 2) unpaved (bare soil) tree pit (UP). We installed 1 m × 1 m treated wooden frames to simulate urban tree pits, 1.5 m apart. We used glyphosate to kill existing herbaceous vegetation and removed it by manually scraping with a spade, but no soil tilling was performed. Subsequent weed growth was suppressed with glyphosate as needed over the two years of the experiment.

To simulate impermeable pavement between the tree pits, we covered the entire plot area outside the pits with 0.254-mm black polyethylene sheeting. This was stapled to the top of the wooden frames to prevent surface water runoff from adjacent areas from entering the tree pits (Fig. 1). We applied a 10-cm layer of woodchips over the black plastic to avoid solarizing the soil. On 11 November, 2014 (Mountains) and 16 December, 2014 (Coastal Plain) we planted at each location 12 *Platanus* × *acerifolia* 'Bloodgood' two-year-old bare-root whips produced from rooted cuttings (Carlton Plants LLC Dayton, OR, USA). Whips were very uniform and approximately 12 mm in diameter at 15 cm above ground. To further standardize tree condition and to minimize soil disturbance at planting, we pruned root systems to

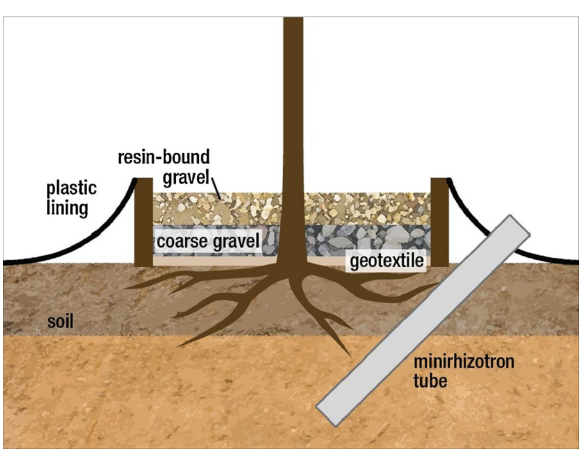

Fig. 1. Tree pit vertical section from porous pavement treatment (PP) showing arrangement of geotextile, gravel base course, and porous pavement as well as minirhizotron location and attachment of plastic sheeting to exclude surface runoff (not to scale).

20 cm × 20 cm × 20 cm volume and whips to 110 cm height. At the Coastal Plain site, two trees did not survive transplanting (one in PP and one in UP) and were replaced with reserved planting stock on 9 July 2015.

Shortly after tree planting, we paved six randomly assigned tree pits for the PP treatment. From soil to pavement surface, this installation included: 1) a sheet of non-woven geotextile (DuPont™ Typar® SF27 90 g m^{-2}, DuPont™ Typar® Geosynthetics, Luxembourg); 2) a 5-cm base course of crushed granite screened to 2.5–4.5 cm (Virginia Department of Transportation #57); and 3) a 5-cm layer of porous-permeable pavement composed of washed pea gravel screened to 9.5 mm, mixed in 20-L batches with 500 mL of Gravel-Lok™ (Cell Tek LLC., Crofton, MD, USA), a polyurethane binder (Fig. 1).

2.3. Tree growth

Tree stem diameter and height were measured in the Coastal Plain site on 9 July, 13 August, 30 October 2015, and 18 May, 12 June, 28 July, 25 August, and 12 October 2016. In the Mountains measurements were taken on 17 July, 12 August, 24 November 2015, and 25 May, 12 June, 24 July, 20 August, 25 September, 23 October 2016, and also on 22 May and 17 June 2017. Stem diameters were measured in two directions (east to west and north to south) at 15 cm above soil surface with calipers (Mitutoyo, Kanagawa, Japan) and averaged for each tree. Tree height was measured with either a height pole or tape on each measurement date except for the first two dates in the Mountains site. At the conclusion of the experiment (October 2016 for the Coastal Plain, and June 2017 for the Mountains) trunk diameter was measured in two directions at 140 cm above the soil line and averaged (DBH). Trees were then cut down at 15 cm above the soil surface, all stems and leaves bagged and oven dried them at 62 °C to a constant weight. In the Mountains, canopy width was also measured in two directions at the conclusion of the experiment.

2.4. Root emergence, depth distribution, and biomass

To assess root appearance and distribution in the soil profile, we installed cellulose acetate butyrate minirhizotron tubes (5-cm i.d. × 85-cm l; Bartz Technology, Santa Barbara, CA, USA) in the ground at a 45° angle with the surface, on the west side (Mountains) or south side (Coastal Plain) of each tree. Tubes were installed 50 cm away from the trunk, and angling toward the tree. Measurements were taken approximately twice monthly between June and November 2015, and between April and August 2016. On each date, we recorded 49 images (frames) per tube with a minirhizotron camera (BTC 100X camera, BTC I-CAP image capture system, Bartz Technology, Santa Barbara, CA, USA), and classified each frame as having roots present or not. In the Mountains, at the end of the experiment in June 2017, we lifted the pavement and geotextile from the tree cutouts to measure the presence of superficial roots. We painted blue all roots visible on the surface that had a diameter greater than 5 mm. We then photographed all tree pits and analyzed the images with Adobe Photoshop CS6 (Adobe Systems, Inc., San José, CA, USA) to calculate the amount of cutout surface covered by roots. Finally, at both sites we excavated the root systems within the 1-m^2 tree cutouts using an air excavation tool (AirSpade 2000, Guardair Corporation, Chicopee, MA, USA at the Coastal Plain site, and Air Knife X-LT, Supersonic Air Knife, Inc., Allison Park, PA, USA at the Mountains site) to expose the root systems, which we then cut flush with the tree pits. We washed the roots, classified them by diameter class (> 2 mm, 2–10 mm, > 10 mm + stump), and then oven dried them at 62 °C to a constant weight.

2.5. Soil water content and temperature

We monitored soil water content and temperature at one replicate per treatment by installing Decagon 5TM capacitance soil sensors

(Decagon Devices, Inc., Pullman, WA, USA) at 10-, 30- and 60-cm depths. Data were logged at 3-h intervals (Model CR1000 Campbell Scientific, Inc., Logan, UT, USA) between July and December 2015. After January 2016, data were logged every 15 min. During rain events, data were collected at 5-min intervals, triggered with a Decagon LWS leaf wetness sensor (Decagon Devices, Inc., Pullman, WA, USA). In each of the remaining 10 tree pits, we measured volumetric soil moisture at depths of 10, 20, 30, 60 and 100 cm with a PR2/6 capacitance probe and DL6 datalogger (Delta-T Devices Ltd., Cambridge, United Kingdom). At the Mountain site we sampled each tree pit twice a month between July and December 2015, and approximately every week between January and September 2016. In the Coastal Plain, we sampled each tree pit with the PR2/6 probe a total of 10 times between July 2015 and September 2016. Also, starting in April 2016, soil water content was sampled with a PR2/6 capacitance probe and DL6 datalogger at four locations under the plastic covering among the tree pits at both sites. No supplemental irrigation was applied throughout the experiment, except in the Mountains on 27 August 2016 and 27 September 2016, when we applied 40 l of water to each tree pit as part of an additional experiment on that plot. Weather data were obtained from on-site monitoring equipment.

2.6. Statistical analysis

We employed *t*-tests to compare PP vs UP differences for mean values of root dry weight, DBH, above-ground dry weight, height, and canopy spread. Trunk diameter at 15 cm from soil surface was analyzed using repeated measures ANOVA, pavement treatment being the between subjects effect, and date of measurement the within subjects effect. For the proportion of minirhizotron frames with roots visible (for a given date and depth), for surface root area, and for soil water content, data were not normally distributed and were analyzed with the nonparametric Wilcoxon Rank Sums test. We performed all analyses with JMP Pro 13 (SAS Institute, Cary, NC, USA). In the Coastal Plain, because one tree in each treatment died and was replaced, we only considered 5 replicates for biomass measurements, but we included all 6 replicates for minirhizotron and soil water content and temperature data.

3. Results

3.1. Root emergence patterns

At both sites, the very first appearance of roots in minirhizotron frames occurred slightly earlier in PP tree pits (Fig. 2). In the colder climate of the Mountains, trees in PP exhibited a clear pattern of earlier and more aggressive root development. Trees in UP took 79 days (June 24–September 11, 2015) to show a similar proportion of minirhizotron frames from the beginning of root monitoring. Also, roots of PP trees in the Mountains were not only visible through the minirhizotrons earlier than in UP, but there were very few frames with roots visible in UP for over a month from the initial date of root monitoring, compared with PP. In the Mountains, the period of greatest increase in minirhizotron frames with visible roots (i.e., the main flush) appeared in PP about two weeks earlier than in UP in the first summer, and one month earlier in the second summer (Fig. 2). In addition, in PP this main flush also resulted in a larger proportion of minirhizotron frames with roots compared with UP: 32% (SE = 9) vs 22.8% (SE = 7), respectively, in the first growing season (see Mountains − July 23, 2015 in Fig. 4 for statistics).

Compared with the mountains, root emergence and growth patterns differed in the Coastal Plain. At the first observation date (July 2015), only the trees in PP had roots visible through the minirhizotrons (Fig. 2. See Fig. 4 for statistics). However, a month later, UP pits had already a higher proportion of minirhizotron frames with roots visible than those in PP, and this trend was maintained for the remainder of the first growing season [6.5% (SE = 3) vs 2.7% (SE = 2) for UP and PP, respectively for 30 October 2015]. In the second growing season, the proportion of minirhizotron frames with roots visible was similar for both treatments in the Coastal Plain (Fig. 2. See Coastal Plain in Fig. 4 for July and August 2016 statistics).

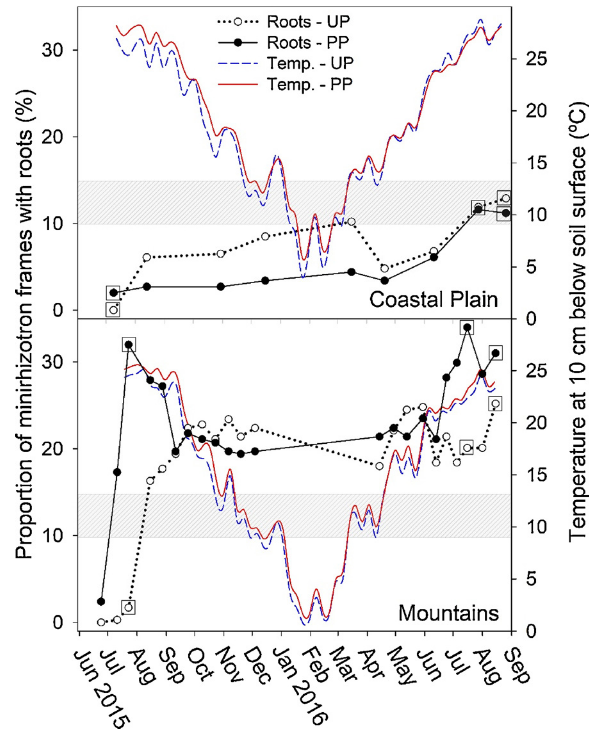

Fig. 2. Soil temperature and change over time in the proportion of all minirhizotron frames (294 per treatment) that had visible roots over the first two growing seasons after planting at two experiment locations. Soil temperature is displayed as a weekly average (n = 1). Shaded area shows estimated temperature range above which root growth occurs for *Platanus* × *acerifolia*. Associated statistics for root data on dates marked with a box are given in Fig. 4.

3.2. Vertical root distribution

There was strong evidence that PP resulted in shallower root systems. At the end of the experiment, trees in PP at both sites had many visible surface roots directly under the pavement, whereas trees in UP had virtually no visible surface roots. In the Mountains, surface roots of trees in PP occupied an average area of 366 cm^2 within the 1-m^2 tree cutout, compared with only 7 cm^2 for trees in UP (Fig. 3, Table 1 and Fig. S1 in Supplemental images). At both sites, roots of PP trees were visible earlier in minirhizotrons in the first 20 cm of soil (Fig. 4). This effect was more pronounced in the Mountains, where we observed a root appearance gradient from top to bottom of the soil profile, which evens out as the "rooting front" moves away from the tree (Fig. 4). In the Coastal Plain, after the initial appearance of roots, minirhizotron data did not show a clear difference between treatments for root depth distribution, contrary to the surface roots that were observed at harvest time for trees in PP. During excavation; however, sinker roots were noted in both treatments. We observed that these sinker roots largely penetrated to a depth of approximately 40–50 cm, although roots of one tree in PP penetrated to a depth of 1.5 m and one tree in UP had one root down to 2.4 m, in the water table. In the Mountains, roots appeared initially in PP at a similar distance from the pavement surface (about 10–20 cm, pavement being 10-cm thick) as they did in UP from the exposed soil surface (Fig. 4, on July 23, 2015). In the Coastal Plain this pattern is not as clear. By the end of the experiment, root presence

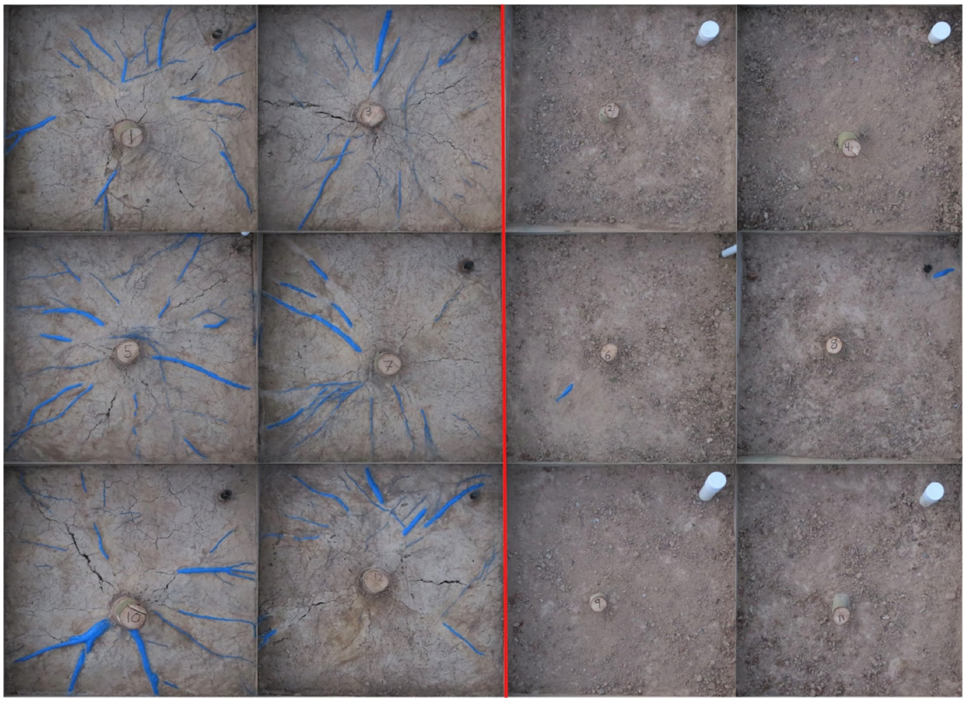

Fig. 3. Photographs of surface roots (painted blue) of *Platanus* × *acerifolia* 'Bloodgood' trees in tree pits with porous pavement (PP) after pavement removal (left, first two columns) and unpaved tree pits (UP, at right), at the Mountains site at the end of the experiment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

became more uniform both in terms of depth distribution and proportion of minirhizotron frames with visible roots at both sites. However, in the Mountains there were more roots present in UP than in PP at deeper minirhizotron frames (38–47 cm) in the second growing season, even though earlier in the experiment there were more roots in PP (Fig. 4). This may suggest further root development at deeper depths for trees in UP. By August of the second summer, the proportion of minirhizotron frames with roots at 38–47-cm depth was 26% (SE = 12) for PP and 30% (SE = 15) for UP in the Mountains, and 2% (SE = 2) for PP vs 11% (SE = 6) for UP in the Coastal Plain. Also in August 2016, at 0–10-cm depth, the proportion of minirhizotron frames with roots was 27% (SE = 8) for PP and 17% (SE = 8) for UP in the Mountains, and 22% (SE = 6) for PP vs 18% (SE = 7) for UP in the Coastal Plain.

3.3. Soil water content and temperature

In the Mountains, average volumetric soil water content (VWC) at 10 cm below the soil surface in PP was higher (Prob > ChiSq = 0.042) than in UP during most of the first growing season (July–October 2015), especially during periods without rainfall. For example, minimum VWC (PR2 sensor) was 0.24 (SE = 0.01) in PP and only 0.18 (SE = 0.005) in UP in September 2015 (Fig. 5). At the end of the second growing season, however, this trend appeared to reverse: soil water content at 10 cm was lower in PP than in UP at times (Fig. 5), although

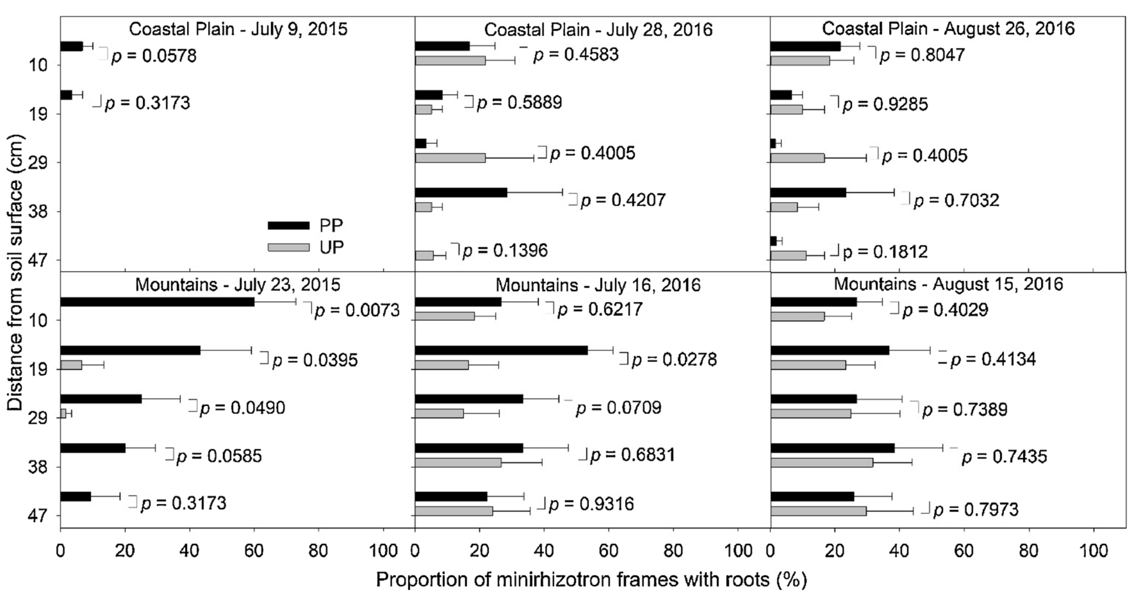

Fig. 4. Proportion of minirhizotron frames with roots visible at selected time periods at 5 soil depths, for *Platanus* × *acerifolia* 'Bloodgood' planted in simulated tree pits with porous pavement (PP) and bare soil treatments (UP), at two locations. Periods illustrated include: initial root appearance (for Coastal Plain, July 9, 2015; for Mountains, June 24, 2015 – data not shown); main flush of roots (for Coastal Plain, July 28, 2016; for Mountains, July 23, 2015 and July 16, 2016); and at the end of the experiment. These dates are the same as for the data points enclosed in boxes in Fig. 2. Each soil depth interval includes 10 minirhizotron frames, except 39–47 cm which includes 9. Error bars represent the standard errors of the means (n = 6).

Table 1
Effect of pavement type (porous pavement-PP, unpaved-UP) on several tree growth parameters and on the presence of surface roots for *Platanus* × *acerifolia* 'Bloodgood' at the end of the experiment in the Coastal Plain (October 2016, n = 5) and in the Mountains (June 2017, n = 6). Canopy spread and surface roots were not sampled in the Coastal Plain.

		Mountains			Coastal Plain		
		Average	SE	Prob > |t|	Average	SE	Prob > |t|
Above ground dry weight (g)	PP	10633.00	552.82	0.0002*	8196.20	763.84	0.0007*
	UP	6350.90	463.89		2875.00	538.35	
Root dry weight (g) total	PP	2016.51	90.32	0.0021*	2094.20	133.75	0.0018*
	UP	1442.34	105.57		1116.60	162.70	
Root dry weight (g) diameter < 2 mm	PP	41.39	3.17	0.0325*	31.80	7.10	0.1214
	UP	26.72	4.82		17.60	3.12	
Root dry weight (g) diameter 2–10 mm	PP	175.39	12.96	0.0019*	172.00	17.00	0.1558
	UP	107.39	7.81		132.40	18.68	
Root dry weight (g) dia. > 10 mm + stump	PP	1799.73	77.58	0.0034*	1890.40	139.26	0.002*
	UP	1308.23	100.17		966.60	150.49	
Height (cm)	PP	432.91	8.72	0.0868	489.40	3.06	0.0039*
	UP	398.78	15.16		354.00	23.08	
Trunk diameter at 140 cm (mm)	PP	55.66	2.02	0.0012*	56.48	1.27	0.0006*
	UP	41.68	2.36		31.32	3.17	
Canopy spread (cm)	PP	342.27	6.79	0.0274*	–	–	–
	UP	304.38	12.24		–	–	
Surface root area visible (cm^2)	PP	365.91	45.52	0.0033*	–	–	–
	UP	6.46	4.12		–	–	

* $p < 0.05$ for *T*-tests and for Wilcoxon Rank Sums test (surface root area visible only – prob > ChiSq).

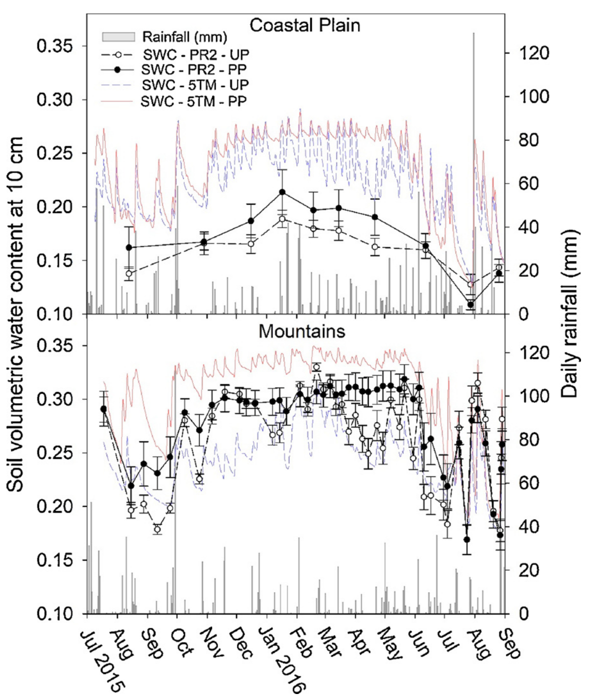

Fig. 5. Change in soil volumetric water content at 10 cm below soil surface for simulated tree pits (1 m^2 each) planted with *Platanus* × *acerifolia* 'Bloodgood', with porous pavement (PP) and bare soil treatments (UP), at two experiment locations. 5TM lines represent daily average soil volumetric water content, n = 1. PR2 lines represent average soil volumetric water content on the dates represented, n = 5; error bars represent standard errors of the means. Gray bars show daily precipitation.

no statistical difference was found at this time (Prob > ChiSq = 0.1524). At the other observed soil depths (data not shown), average soil water content was similar. In the Coastal Plain, volumetric soil water content patterns were similar to those at the Mountains site, although differences between treatments were reduced. As trees grew, especially during dry periods, as in July 2016 (Fig. 5), the lower soil moisture values for PP also suggest greater water withdrawal by the larger roots systems of trees in pavement, rather than because of drainage or lack of water movement. At both sites, soil water content is less variable over time at 10 cm below soil surface for PP than for UP. During a warm spell in April 2016, prior to trees leafing out, soil water content decreased sharply in UP, especially in the Mountains, but remained stable in the PP treatment. Also, soil moisture depletion rates by tree water uptake in late spring and early summer are similar for both treatments at both sites, especially in the Coastal Plain.

At both sites, differences in soil temperature at 10-cm depth were greater in fall than in spring, PP being warmer than UP in all cases but the second summer in the Coastal Plain (Fig. 2). This trend also shows at a 30- and 60-cm depth (Fig. S2 in Supplemental images). At the Mountains site, at 10-cm depth, UP and PP soils appeared to cool down and warm up at similar rates in fall and spring. However, in October of the first growing season there was a warm spell and soils in PP heated more quickly than soil in UP. In spring, under two consecutive warm spells (April–May 2016), this trend disappeared, and both PP and UP soils at 10-cm depth showed similar net temperature gain. However the PP treatment remained warmer during the period between the two warm spells. In fall, UP soil was generally colder until November, when soil temperatures become similar between the two treatments. At 30- and 60-cm depths, temperature is warmer in PP during spring and summer (Fig. S2 in Supplemental images). In the Coastal Plain, soils in both treatments warmed up at similar rates in spring, but in fall UP cooled faster than PP. The average soil temperature at 10-cm depth in October 2015 was 1.1 °C (Mountains) and 1.2 °C (Coastal Plain) higher in PP than in UP. Also, the number of days with soil temperature at 10-cm depth equal or greater to 25 °C was greater in PP than in UP in the first growing season, with 31 vs 11 days in the Mountains, and 68 vs 50 days in the Coastal Plain. In the second growing season, there were 11 (PP) and 1 (UP) days in the Mountains, and 74 (PP) and 82 (UP) days in the Coastal Plain. Under peaks of hot or cold weather, weekly temperature variations were more obvious in the Coastal Plain than in the Mountains, and UP cooled down and warmed up faster than PP. This is probably a consequence of the lower thermal inertia of the sandier soils

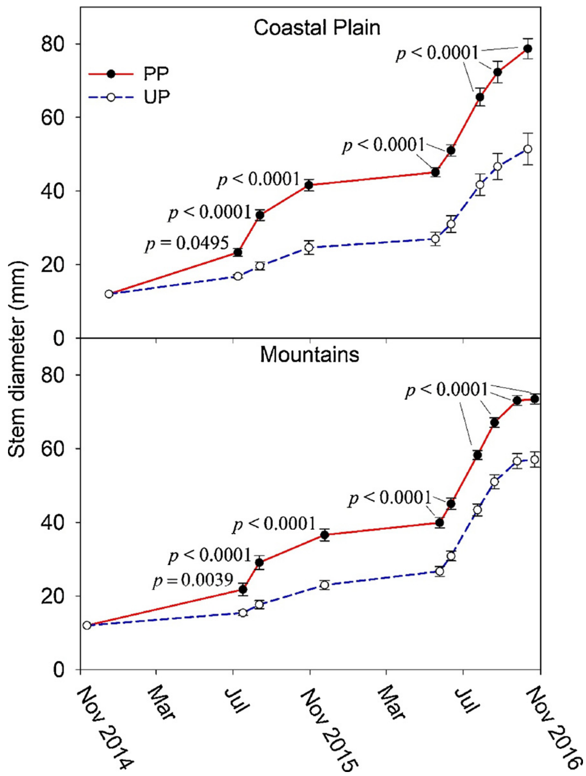

Fig. 6. Change in stem diameter measured at 152 mm above soil surface, of *Platanus* × *acerifolia* 'Bloodgood' trees planted in simulated tree pits with porous pavement (PP) and bare soil treatments (UP), at two experiment locations, during the first two growing seasons after planting. Error bars represent the standard errors of the means (n = 6 in Mountains, n = 5 in Coastal Plain).

at the Coastal Plain site.

3.4. Root biomass

At both sites, trees had greater root biomass in PP than in UP, with specific increases of 87% in the Coastal Plain and 40% in the Mountains (Table 1). This was true for all three diameter classes, despite the greater amount of roots left behind outside of the tree pits in PP than in UP (based on visual assessment, as we only harvested the roots within the cutouts).

3.5. Above-ground tree growth

Trees grew larger and faster in PP than in UP at both sites (Fig. 6, and Figs. S3 and S4 in Supplemental images), especially during the first growing season. In the Coastal Plain, at the end of the first growing season (October 2015) average trunk diameter of trees in PP was 69% greater than in UP [41.6 mm (SE = 1.6) for PP; 24.6 mm (SE = 1.9) for UP] (Fig. 6), and average tree height was 42% greater [263.3 mm (SE = 3.1) for PP; 185.2 mm (SE = 8.0) for UP; Fig. S3 in Supplemental images]. However, after two growing seasons (October 2016, Table 1 and Fig. S4 in Supplemental images), the magnitude of these differences in the Coastal Plain were not as large: average stem diameter was only 53% greater in PP [78.7 mm (SE = 2.7) for PP; 51.43 mm (SE = 4.3) for UP] and average tree height was 41% greater in PP [499.4 mm (SE = 3.1) for PP; 354 mm (SE = 23.1) for UP]. In the Mountains, tree average stem diameter (Fig. 6) and average height in PP were also larger, but the magnitude of these differences was not as great and narrowed more quickly: average trunk diameter was 59% greater in PP [36.59 mm (SE = 1.6) for PP; 22.98 mm (SE = 1.2) for UP], while average height was 54% greater [232.5 mm (SE = 10.2) for PP; 150.83 mm (SE = 10.9) for UP] after the first growing season (November 2015). However, by October 2016, at the Mountain site average trunk diameter was 29% greater [73.49 mm (SE = 1.3) for PP; 57.34 mm (SE = 2.1) for UP] and average height was only 19% greater [407.17 mm (SE = 8.9) for PP; 340.83 mm (SE = 14.3) for UP] Fig. 6 and Table 1. Trunk diameter variability within treatments increased with time in the Coastal Plain. However, in the Mountains, this variability within treatments only increased slightly for UP, and actually decreased for PP (Fig. 6). In the Mountains, at final harvest time (June 2017), average trunk diameter and average height are only 28% and 9% greater in PP than in UP, respectively (Table 1). Although still significant, the smaller magnitude of these differences between PP and UP for average trunk diameter and average height (compared with 59% and 54% greater in November 2015), suggest trees in UP may have been catching up with those of trees in PP. Nonetheless, at harvest time average DBH and average above ground dry biomass were greater for trees in PP than for trees in UP, by 34% and 67% in the Mountains, and by 80% and 185% in the Coastal Plain, respectively. Final average canopy width in the Mountains was also 12% greater for the PP treatment (Table 1).

4. Discussion

Porous pavement (PP) resulted in faster establishment, with roots emerging significantly earlier in the growing season. Transplant season may alter time of root emergence in the spring (Harris et al., 1995). At both sites, however, trees were planted in late fall, when little or no root growth likely occurred, suggesting that PP may reduce the time from transplant to root initiation, and thus to establishment. A measure of tree establishment after transplant is the recovery of the branch to root spread ratio (Watson, 1985). The faster and more ubiquitous root appearance in the minirhizotrons in PP in the first growing season after transplant at the Mountains site, and the increased trunk diameter for trees in PP at both sites, support the idea of PP promoting establishment. In the nursery industry, establishment period has been referred to comprising of three phases: 'sleep' (little growth the first year after transplant); 'creep' (moderate growth the second year); and 'leap' (rapid growth in the third year) (Harris, 2007). In our study, the 'sleep' phase in the first growing season is not evident in either treatment, probably because we used an easy-to-transplant species and the trees were very young at planting time. Trees in UP were in the 'creep' phase, and trees in PP were already starting to 'leap', especially in the Coastal Plain site, while in the second growing season, trees in both PP and UP appeared to be in the 'leap' phase.

The porous pavement and gravel base in PP had a mulch-like effect, reducing soil water loss and minimizing soil heat loss during cold periods. In the Mountains, this interpretation is also supported by the apparent enhanced survival of trees in PP compared with trees in UP after the first winter: two trees in UP died back to about 20 cm from the soil surface, whereas all six trees in PP were undamaged. January 2015 had temperatures as low as −23 °C, so this effect may not be as relevant at sites with warm climates, where low winter temperatures are not an issue for fall transplanting. In the Mountains, with a colder climate and a finer soil texture, the observed root development lag phase for UP vs PP was much clearer than in the Coastal Plain (Fig. 2). Because tree roots are sensitive to temperature, roots under the PP treatment in the Mountains may, over time, be following a soil isotherm downward (see all three sampling dates in Fig. 4), as suggested by Kaspar and Bland (1992).

Soils under PP were warmer at 10-cm depth, except towards the end of the second growing season in the Coastal Plain, where soil at 10-cm, 30-cm and 60-cm depths under PP was cooler than for UP, possibly because of the shading caused by the larger canopies of trees in PP, as was seen in Volder et al. (2009). Also, although in the first growing season there were more days in PP with daily average soil temperature at 10-cm depth equal or above 25 °C, in the second growing season UP had more of those warmer days (82 vs 74), further supporting the idea of the shading effect by the larger trees in PP. Thus, any increase in the length of the growing season for roots, or potential damage to roots by excessive heat, may be less relevant for mature trees, or at other sites where the pavement is shaded. Warmer soil temperature induced by PP seems to benefit *Platanus × acerifolia* 'Bloodgood' at both locations in our study. However, soil temperatures greater than 30 °C are detrimental to root growth for most temperate tree species (Graves, 1994). Since soil temperature at 10-cm depth stayed well above 25 °C for several months in summer in the Coastal Plain, at locations with longer and hotter summers soil temperature directly under the pavement may be too high for root growth if tree canopy is not yet large enough to shade the paved area, and if pavement has low albedo.

In general, soil warms up from top to bottom in spring (also see Fig. S2 in Supplemental images), and root emergence near the surface occurs earlier than in lower, colder regions of the soil. In addition, the PP cover might help accelerate heating up the soil in spring in finer-textured soils, as well as maintaining higher soil temperatures further into the fall season. However, in this sense, pervious pavement behaves differently from mulches in that spring soil temperatures were greater (1–2 °C) in PP compared with UP, while mulches have been shown to delay soil warming in cold soil regions (Greenly and Rakow, 1995). This result suggests that PP may provide a longer root growing season in colder climates, possibly affecting tree establishment rates (Struve, 2009). Fini et al. (2017) suggested that pavements with lower albedo than soil, as in our experiment, may partly explain the soil warming effect (Fig. S5 in Supplemental images). Such temperature differences may also help explain the contrasting patterns of root emergence we observed, especially in the Mountains, where PP showed an earlier and stronger flush of roots. In the Coastal Plain, temperature patterns similar to those in the Mountains were observed, but a direct relationship of temperature-to-root flush was not evident in the minirhizotron data. At both sites, some decreases in root visibility were probably attributed to observational uncertainties, due to soil moving into the air pockets by the minirhizotron wall, covering previously visible roots. However, it is possible that there was also some root turnover late in the summer associated with the leaf drop that is characteristic of Platanus at that time of the year.

At the Coastal Plain site, unlike in the Mountains, we observed a greater proportion of minirhizotron locations with roots in UP than in PP for most of the experiment, even though PP trees were considerably larger. This difference between sites may have to do with minirhizotron tubes being perhaps less of a preferential root path (Taylor and Bohm, 1976; Hendrick and Pregitzer, 1996) at the Coastal Plain site because of the coarser soil texture, which leaves fewer gaps around the tube wall during minirhizotron installation. During root excavation at the mountain site, several roots were found following up or down the wall of the minirhizotron tubes, but this was not observed at the Coastal Plain site.

In our study, both minirhizotron data and observed surface rooting patterns indicate that *Platanus × acerifolia* 'Bloodgood' develops a significantly shallower root system under PP compared with UP, perhaps due to the greater soil moisture levels under pavement as the roots were developing. Soils in our study were not compacted, and lower soil horizons had relatively low bulk densities and likely did not restrict rooting depth. This superficial root development under porous pavement was also noted by Morgenroth (2011) in *Platanus orientalis* under similar prevailing conditions (i.e., higher soil water contents under pavement). Shallower tree rooting might have implications for sidewalk and infrastructure damage (Kopinga, 1994; McPherson et al., 2000; Randrup et al., 2001), and for the resilience of urban trees to climate change. However, for all trees at both sites, regardless of treatment within the pit, tree roots grew up to the soil surface once they were out of the tree pit and under the impermeable area of the plot (i.e., under plastic). Thus, beyond the establishment period, rooting depth will be controlled by the soil and pavement conditions surrounding the tree pit, unless the tree pits are very large.

PP consistently resulted in larger trees compared with those in UP, which may lead to an earlier ecosystem service provision by trees in PP (McPherson et al., 1994; Mullaney et al., 2015b). However, the degree of tree response to PP, and the duration of the PP effect may vary depending on climate, soil and overall site and design characteristics (e.g., size of pits, albedo of pavement, etc.). For example, at the Mountains site trunk diameter variability within PP decreased over time while it increased at the Coastal Plain site (Fig. 6). This homogenization of the population at the Mountain site could suggest that, for a site more limiting for tree growth (as in the Mountains compared with the Coastal Plain), soil water and temperature changes associated with PP are a more dominant influence than other site factors. Because of the periodic nature of our measurements, it is not possible to determine the proportion of variability in root growth explained by soil temperature and soil water content. Nonetheless, comparison of root growth patterns at the two sites suggests the importance of soil temperature and water content. Fini et al. (2017) found no difference in trunk diameter by pavement treatment for *Celtis australis*, and only initially greater diameter for *Fraxinus ornus* in an impervious pavement treatment. Although that study also looked at establishing trees in 1-m^2 tree pits, the pavement treatment was outside the tree pits, while all treatments had bare soil within the pit. Thus, effects on establishment may be more pronounced when pavement is over the soil where the new roots are developing (i.e. the rooting front).

Besides the pavement effect on temperature, these responses of young transplanted *Platanus × acerifolia* 'Bloodgood' to PP are likely also a function of the pavement effect on soil moisture. During the first growing season, surface soils had higher water contents at shallow depths under PP compared with UP, as also noted by Morgenroth and Buchan (2009), Morgenroth et al. (2013) and Fini et al. (2017). However, soil moisture depletion rates by tree water uptake in late spring and early summer are similar for PP and UP, especially in the Coastal Plain, possibly because evaporation in UP makes up for the reduced tree water uptake of smaller UP trees compared with PP. The reduction in soil water evaporation provided by the pavement is evident during a warm spell in April 2016, when soil water content decreases sharply in UP, but remains stable in PP. This happened right before trees leafed out later in April, reducing the amount of available water at 10 cm depth for trees in UP as they start to grow in spring. At both sites, soil water content at 10-cm depth in PP is lower during dry periods in the second summer compared with the first summer, presumably due to the increased presence of surface roots in PP. These results suggest that once root systems explore the soil directly under pavement, increases in soil water content may dissipate as was observed by Volder et al. (2009). The greatest effect of PP on soil water content, and thus, on root growth may be at the interface of soil yet unexplored by roots and the advancing "rooting front". While this more readily available water appears to promote accelerated tree growth, deeper root systems of UP trees may confer advantages during dry periods. In the Mountains soil water content was lower in UP at 100-cm depth, by the end of the experiment, supporting our observation of deeper root systems for trees in UP. However, both *Platanus × acerifolia* 'Bloodgood' parents (*Platanus occidentalis* L. and *Platanus orientalis*) are bottomland species, and its root growth may be very responsive to soil moisture and the associated reduction of soil strength that occurs in finer-textured soils (Day et al., 2000). Young trees that are not bottomland species may not have as strong of a root growth response to the effects of PP on soil moisture, because the soil could be too wet for root penetration when soil strength is sufficiently low, especially if soils beneath pavement are heavily compacted.

PP in tree pits increased tree establishment and growth, as well as promoted shallower root systems, compared with trees planted in pits with no pavement cover. Although the Coastal Plain site had mild winters and hotter summers relative to the Mountain site, both experimental sites have a distinct winter with cold temperatures, and ample rainfall. It is possible that soil temperature may always be favorable for root growth at sites with little winter, and PP might not promote faster root growth compared with bare soil. In this case, PP with low albedo may even be detrimental and may heat up the soil excessively (Celestian and Martin, 2004). Pea gravel, as was used in our study to formulate the porous pavement, has an albedo between 0.12 and 0.34 depending upon color, similar to or lower than bare soils and somewhat lower than concrete (Reagan and Acklam, 1979). Since the resin-coating process darkens the gravel slightly, PP in our study was likely on the lower end of this spectrum. At sites with very dry climates, we would anticipate that the effect of increased soil water content of PP at shallow depths may still be present, but it is possible that there could be periods of time (summer), when there will not be enough soil moisture available to cause the distillation effect under the pavement. As a consequence, roots that had proliferated near the soil surface while moisture was sufficient may have reduced access to water. However, to our knowledge these effects have not been studied at this time.

Transplanted urban trees are often balled and burlapped stock that are larger than the trees used in our study. Thus, the smaller size of the trees used in this study may mean that their roots were more heavily influenced by the characteristics of the tree pit during establishment than larger trees would be in a similarly-sized pit. On the other hand, many cities now routinely have considerably larger tree pits, meaning even larger stock would be heavily influenced by pit surface conditions. Further research with taxa less vigorous than *Platanus* × *acerifolia* 'Bloodgood', and in other climate types, particularly very dry, hot or cold climates, is necessary to strengthen our understanding of these pavement systems.

Many cities are now experimenting with increased areas of porous pavement around street trees. This creates an opportunity to design pavement sections (a cross-section of the layers that make up a soil/pavement installation) that will direct root growth to both reduce pavement/root conflicts and increase drought resilience. Porous pavement over a base course and non-compacted soil may create favorable rooting conditions (higher soil water contents, warmer but moderated temperatures, moderate soil strength). Thus, employing porous pavement around tree pits, instead of impermeable, could promote tree rooting and growth beyond the establishment period, increase ecosystem service provision by trees, and reduce stormwater runoff generation, particularly when measures to avoid soil compaction are taken.

5. Conclusions

Porous pavement installations in tree pits can promote faster establishment of *Platanus* × *acerifolia* 'Bloodgood' trees, with earlier root emergence after transplanting. Porous pavement also resulted in increased growth rates, larger root systems and canopies, but also shallower roots compared with trees in bare soil, potentially affecting drought resilience. These effects were likely due to the favorable rooting environment created by increased soil water contents and temperatures in surface soils under porous pavement. Therefore our findings are best understood in terms of the interaction of the pavement section (including both pavement design and soil conditions) with climate, as well as with the tree development stage, which influences the amount of soil explored by roots. These interactions may explain the sometimes contradictory results of studies reporting tree response to porous pavement. In addition, the rooting environment may be dominated by other types of soil surface covers after the establishment period, such as by impermeable pavements that occur beyond the planting pit. Nonetheless, our study suggests that whether the increase in growth we observed with porous pavement will persist over time may depend on site characteristics, especially after roots have explored beyond the tree pit area.

Acknowledgements

This study was funded in part by the Virginia Tech Department of Horticulture, the Virginia Urban Forest Council, Virginia Agricultural Experiment Station and the Hatch Program of the National Institute of Food and Agriculture, U.S. Department of Agriculture. We also thank John Peterson, John James, Lisa Goodell, and Velva Groover for their assistance.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ufug.2018.05.003.

References

Berland, A., Shiflett, S.A., Shuster, W.D., Garmestani, A.S., Goddard, H.C., Herrmann, D.L., Hopton, M.E., 2017. The role of trees in urban stormwater management. Landsc. Urban Plan. 162, 167–177. http://dx.doi.org/10.1016/j.landurbplan.2017.02.017.

Celestian, S.B., Martin, C.A., 2004. Rhizosphere, surface, and air temperature patterns at parking lots in Phoenix, Arizona, US. J. Arboric. 30, 245–252.

Crow, P., 2005. The Influence of Soils and Species on Tree Root Depth. Information Note FCINO78. For. Res. Edin.: For. Comm., UK.

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 Green. 10, 317–322. http://dx.doi.org/10.1016/j.ufug.2011.08.001.

Day, S.D., Seiler, J., Persaud, N., 2000. A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiol. 20, 257–263. http://dx.doi.org/10.1093/treephys/20.4.257.

Day, S.D., Wiseman, P.E., Dickinson, S.B., Harris, J.R., 2010a. Contemporary concepts of root system architecture of urban trees. Arboric. Urban For. 36, 149–159.

Day, S.D., Wiseman, P.E., Dickinson, S.B., Harris, J.R., 2010b. Tree root ecology in the urban environment and implications for a sustainable rhizosphere. J. Arboric. 36, 193.

Fini, A., Frangi, P., Mori, J., Donzelli, D., Ferrini, F., 2017. Nature based solutions to mitigate soil sealing in urban areas: results from a 4-year study comparing permeable, porous, and impermeable pavements. Environ. Res. 156, 443–454. http://dx.doi.org/10.1016/j.envres.2017.03.032.

Fitzgerald, J., Laufer, J., 2017. Governing green stormwater infrastructure: the Philadelphia experience. Local Environ. 22, 256–268. http://dx.doi.org/10.1080/13549839.2016.1191063.

Grabosky, J., Gilman, E., 2004. Measurement and prediction of tree growth reduction from tree planting space design in established parking lots. J. Arboric. 154–164.

Graves, W.R., 1994. Urban soil temperatures and their potential impact on tree growth. J. Arboric. 20 24–24.

Greenly, K.M., Rakow, D.A., 1995. The effect of wood mulch type and depth on weed and tree growth and certain soil parameters. J. Arboric. 21 225–225.

Harris, J.R., Bassuk, N.L., Zobel, R.W., Whitlow, T.H., 1995. Root and shoot growth periodicity of green ash, scarlet oak, Turkish hazelnut, and tree lilac. J. Am. Soc. Hortic. Sci. 120, 211–216.

Harris, J.R., 2007. Transplanting large trees. CAB Rev. 2http://dx.doi.org/10.1079/PAVSNNR20072024. (7 pp).

Hendrick, R.L., Pregitzer, K.S., 1996. Applications of minirhizotrons to understand root function in forests and other natural ecosystems. Plant Soil 185, 293–304. http://dx.doi.org/10.1007/bf02257535.

Iakovoglou, V., Thompson, J., Burras, L., Kipper, R., 2001. Factors related to tree growth across urban-rural gradients in the Midwest, USA. Urban Ecosyst. 5, 71–85. http://dx.doi.org/10.1023/A:1021829702654.

Kaspar, T.C., Bland, W.L., 1992. Soil temperature and root growth. Soil Sci. 154, 290–299.

Kevern, J., Schaefer, V., Wang, K., 2009. Temperature behavior of pervious concrete systems. J. Transp. Res. Board 94–101. http://dx.doi.org/10.3141/2098-10.

Kevern, J.T., Haselbach, L., Schaefer, V.R., 2012. Hot weather comparative heat balances in pervious concrete and impervious concrete pavement systems. J. Heat Isl. Inst. Int. 7, 2012.

Kjelgren, R.K., Clark, J.R., 1994. Urban microclimates and growth of sweetgum street trees. Arboric. J. 18, 401–417. http://dx.doi.org/10.1080/03071375.1994.9747045.

Kopinga, J., 1994. Aspects of the damage to asphalt road pavings caused by roots, The Landscape Below Ground. In: Proceedings of an International Workshop on Tree Root Development in Urban Soils. International Society of Arboriculture. Champaign, IL. pp. 165–178.

Livesley, S.J., McPherson, E.G., Calfapietra, C., 2016. The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. J. Environ. Qual. 45, 119–124. http://dx.doi.org/10.2134/jeq2015.11.0567.

Lu, J., Svendsen, E.S., Campbell, L.K., Greenfeld, J., Braden, J., King, K.L., Falxa-Raymond, N., 2010. Biological, social, and urban design factors affecting young street tree mortality in New York City. Cities Environ. 3.

McPherson, G.E., Nowak, D.J., Rowntree, R.A., 1994. Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. USDA NE Exp.

McPherson, E., Costello, L., Perry, E., Peper, P., 2000. Reducing tree root damage to sidewalks in California cities: a collaborative study. Report of the Elvenia J. Slosson Fund for Ornamental Horticulture 1998–1999. pp. 8–12.

McPherson, G., Simpson, J.R., Peper, P.J., Maco, S.E., Xiao, Q., 2005. Municipal forest benefits and costs in five US cities. J. For. 103, 411–416.

McPherson, E.G., Berry, A.M., van Doorn, N.S., 2018. Performance testing to identify climate-ready trees. Urban For. Urban Green. 29, 28–39. http://dx.doi.org/10.1016/j.ufug.2017.09.003.
Morgenroth, J., Buchan, G.D., 2009. Soil moisture and aeration beneath pervious and impervious pavements. Arboric. Urban For. 35, 135–141.
Morgenroth, J., Visser, R., 2011. Aboveground growth response of *Platanus orientalis* to porous pavements. Arboric. Urban For. 37, 1.
Morgenroth, J., Buchan, G., Scharenbroch, B.C., 2013. Belowground effects of porous pavements—soil moisture and chemical properties. Ecol. Eng. 51, 221–228. http://dx.doi.org/10.1016/j.ecoleng.2012.12.041.
Morgenroth, J., 2011. Root growth response of *Platanus orientalis* to porous pavements. Arboric. Urban For. 37, 45.
Mullaney, J., Lucke, T., Trueman, S.J., 2015a. The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees. Urban For. Urban Green. 14, 19–29. http://dx.doi.org/10.1016/j.ufug.2014.11.007.
Mullaney, J., Lucke, T., Trueman, S.J., 2015b. A review of benefits and challenges in growing street trees in paved urban environments. Landsc. Urban Plan. 134, 157–166. http://dx.doi.org/10.1016/j.landurbplan.2014.10.013.
Rahman, M., Stringer, P., Ennos, A., 2013. Effect of pit design and soil composition on performance of *Pyrus calleryana* street trees in the establishment period. Arboric. Urban For. 39, 25.
Randrup, T.B., McPherson, E.G., Costello, L.R., 2001. A review of tree root conflicts with sidewalks, curbs, and roads. Urban Ecosyst. 5, 209–225. http://dx.doi.org/10.1023/A:1024046004731.
Reagan, J.A., Acklam, D.M., 1979. Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern U.S.A. residences. Energ. Build. 2, 237–248. http://dx.doi.org/10.1016/0378-7788(79)90009-4.
Rodríguez-Rojas, M.I., Huertas-Fernández, F., Moreno, B., Martínez, G., Grindlay, A.L., 2018. A study of the application of permeable pavements as a sustainable technique for the mitigation of soil sealing in cities: a case study in the south of Spain. J. Environ. Manag. 205, 151–162. http://dx.doi.org/10.1016/j.jenvman.2017.09.075.
Sanders, J., Grabosky, J., Cowie, P., 2013. Establishing maximum size expectations for urban trees with regard to designed space. Arboric. Urban For. 39, 68–73.
Savi, T., Bertuzzi, S., Branca, S., Tretiach, M., Nardini, A., 2015. Drought-induced xylem cavitation and hydraulic deterioration: risk factors for urban trees under climate change? New Phytol. 205, 1106–1116. http://dx.doi.org/10.1111/nph.13112.
Scalenghe, R., Marsan, F.A., 2009. The anthropogenic sealing of soils in urban areas. Landsc. Urban Plan. 90, 1–10. http://dx.doi.org/10.1016/j.landurbplan.2008.10.011.
Schröder, K., 2008. Root space underneath traffic lanes. Arboric. J. 31, 33–43. http://dx.doi.org/10.1080/03071375.2008.9747516.
Struve, D.K., 2009. Tree establishment: a review of some of the factors affecting transplant survival and establishment. J. Arboric. 35, 10.
Taylor, H., Bohm, W., 1976. Use of acrylic plastic as rhizotron windows [Soybeans, rooting density]. Agron. J. 68, 693–694.
Volder, A., Watson, T., Viswanathan, B., 2009. Potential use of pervious concrete for maintaining existing mature trees during and after urban development. Urban For. Urban Green. 8, 249–256.
Volder, A., Viswanathan, B., Watson, W.T., 2014. Pervious and impervious pavement reduce production and decrease lifespan of fine roots of mature sweetgum trees. Urban Ecosyst. 17, 445–453. http://dx.doi.org/10.1007/s11252-013-0330-3.
Wang, Z., Guo, D., Wang, X., Gu, J., Mei, L., 2006. Fine root architecture, morphology, and biomass of different branch orders of two Chinese temperate tree species. Plant Soil 288, 155–171. http://dx.doi.org/10.1007/s11104-006-9101-8.
Watson, G., 1985. Tree size affects root regeneration and top growth after transplanting. J. Arboric. 11, 37–40.