Water Fluxes in Soil-Pavement Systems: Integrating Trees, Soils and Infrastructure

by
Francisco Javier de la Mota Daniel

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Susan D. Day, Chair
James S. Owen Jr.
Ryan D. Stewart
Meredith K. Steele
Venkataramana R. Sridhar

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Abstract

In urban areas, trees are often planted in bare-soil sidewalk openings (tree pits) which recently are being covered with permeable pavements. Pavements are known to alter soil moisture and temperature, and may have implications for tree growth, root development and depth, drought resilience, and sidewalk lifting. Furthermore, tree pits are often the only unsealed soil surface and are important for water exchange between soil and atmosphere. Therefore, covering tree pits with pavement, even permeable, may have implications for the urban water balance and stormwater management. A better understanding of permeable pavement on tree-pavement-soil system functioning can inform improved tree pit and street design for greater sustainability of urban environments.

We conducted experiments at two sites in Virginia, USA (Mountains and Coastal Plain) with different climate and soil. At each location, we constructed 24 tree pits in a completely randomized experiment with two factors: paved with resin-bound porous-permeable pavement versus unpaved, and planted with *Platanus ×acerifolia* 'Bloodgood' versus unplanted (n = 6). We measured tree stem diameter, root growth and depth, and soil water content and temperature over two growing seasons. We also monitored tree sap flow one week in June 2017 at the Mountains. In addition, we calibrated and validated a soil water flow model, HYDRUS-1D, to predict soil water distribution for different rooting depths, soil textures and pavement thicknesses.

Trees in paved tree pits grew larger, with stem diameters 29% (Mountains) and 51% (Coastal Plain) greater. Roots developed faster under pavement, possibly due to the increased soil water content and the extended root growing season (14 more days). Tree transpiration was 33% of unpaved and planted pit water outputs, while it was 64% for paved and planted pits. In June 2016, planted pits had decreased root-zone water storage, while unplanted pits showed increased storage. A water balance of the entire experimental site showed overall decreased soil water storage due to tree water extraction

becoming the dominant factor. HYDRUS-1D provided overall best results for model validation at 10-cm depth from soil surface (NSE = 0.447 for planted and paved tree pits), compared to 30- and 60-cm depths. HYDRUS-1D simulations with greater pavement thickness resulted in changes in predicted soil water content at the Coastal Plain, with higher values at 10- and 30-cm depths, but lower values at 60-cm depth. At the Mountains, virtually no difference was observed, possibly due to different soil texture (sandy vs clayey).

Tree pits with permeable pavement accelerated tree establishment, but promoted shallower roots, possibly increasing root-pavement conflicts and tree drought susceptibility. Paved tree pits resulted in larger trees, increasing tree transpiration, but reduced soil evaporation compared to unpaved pits. Larger bare-soil pits surrounded by permeable pavement might yield the best results to improve urban stormwater retention. Also, HYDRUS-1D was successful at simulating soil water content at 10-cm depth and may be valuable to inform streetscape design and planning.

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Abstract

Trees in cities are often planted in pavement cutouts (tree pits) that are usually the only available area for water exchange between soil and atmosphere. Tree pits are typically covered with a variety of materials, including permeable pavement. Pavements are known to modify soil water distribution and temperature, affecting tree growth, rooting depth, drought resilience, and sidewalk lifting. A better understanding of this system can inform tree pit and street design for greater sustainability. We constructed 24 tree pits at each of two regions in Virginia, USA (Mountains and Coastal Plain). These tree pits were paved with permeable pavement or unpaved, and planted with London Plane or unplanted. We measured stem diameter, root growth, and soil water content and temperature over two years and tree sap flow for one week in summer (Mountains only). We also used a soil water flow model, HYDRUS-1D, to predict water distribution for different rooting depths, soil textures and pavement thicknesses.

After the first growing season trees in pavement were larger, with stem diameters 29% (Mountains) and 51% (Coastal Plain) greater. Roots developed faster under pavement, possibly due to increased soil water content and a 14-day increase in root growing season. Also, in June 2017, tree transpiration was 33% of unpaved-and-planted pit water outputs, and 64% of paved-and-planted pits. In June 2016, root-zone water storage decreased in planted pits but increased in unplanted pits. When considering the entire experimental site, soil water storage decreased, with tree water extraction being the dominant factor. HYDRUS-1D performed better at 10-cm soil depth than at 30- and 60-cm depths. At the Coastal Plain, HYDRUS-1D predicted higher soil water content at 10- and 30-cm depths with increased pavement thickness, but lower values at 60-cm depth. At the Mountains, there was no effect, possibly due to higher clay content. Permeable pavement accelerated tree establishment, but promoted shallower roots, increasing drought susceptibility and risk for root-pavement conflicts. Pavement resulted in larger trees and greater transpiration, but reduced soil evaporation. Larger bare-soil pits surrounded by permeable pavement might optimize stormwater retention.

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Dedication

To my wife, Lisa, for her daily support.

And to my parents, for their encouragement to persevere.

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Preface

This dissertation represents my doctoral research at Virginia Tech. The dissertation is presented in manuscript format and Chapters 2-4 each represent a manuscript that either has or will be submitted for publication. Chapter 2 has been published in Urban Forestry & Urban Greening (de la Mota Daniel, F.J., Day, S.D., Owen Jr, J.S., Stewart, R.D., Steele, M.K., Sridhar, V., 2018. Porous-permeable pavements promote growth and establishment and modify root depth distribution of *Platanus* × *acerifolia* (Aiton) Willd. in simulated urban tree pits. Urban Forestry & Urban Greening, 33, 27-36 https://doi.org/10.1016/j.ufug.2018.05.003). Chapter 3 will receive additional revisions from expected co-authors and be submitted to Hydrological Processes. Chapter 4 will receive additional revisions from expected co-authors and journal submission is to be determined.

Chapter 1
Introduction and Literature Review

1.1 Background

In highly urban areas, trees are often planted in sidewalk cutouts (tree pits) that have a variety of surface coverings. For at least a decade, resin-bound gravel, a type of pervious pavement, has been used in many cities to fill in tree pits as a means to increase pavement surface for pedestrian use. These installations are taking place more frequently in arid regions. In these regions, weed pressure is low, and as a consequence, no mulch or soil cover has been used in the past. In an increasingly urbanized world, and with frequency of large storm events forecasted to increase in many areas, it is of interest to find out how these systems influence tree growth, stormwater infiltration into the soil, and the overall water fluxes in urban ecosystems.

Urban heat island effects and stormwater runoff due to urbanization have significant impacts on human wellbeing, and the interactions between trees and permeable pavements may have a role in mitigating some of these detrimental effects. My overall goal for this project is to understand the interactions of permeable pavements and urban trees, and to assess how these interactions affect the tree pit system water balance. As a part of this goal, I will analyze the potentially modified patterns of soil water movement and tree root growth under these porous pavements, and I will evaluate the ability of the model HYDRUS-1D to simulate water fluxes in these tree-pavement systems, so that we can make predictions for different soil-pavement profiles and climate scenarios, to inform sustainable streetscape design that integrates trees.

1.2 Literature review

1.2.1 Trees in dense urban environments

Trees growing in dense urban areas provide many ecosystem services including stormwater runoff reduction through canopy rainfall interception and water infiltration into the soil, urban heat island mitigation through shading, wildlife habitat, and increased emotional well-being (McPherson et al., 2005; Nowak and Dwyer, 2007; Mullaney et al., 2015b; Livesley et al., 2016; Berland et al., 2017). These dense urban areas are characterized by a predominantly paved environment, resulting in trees growing in cutouts in the pavement usually referred to as tree pits. These growing conditions pose many challenges to tree health (Patterson, 1977; Hawver and Bassuk, 2007) and survival (Lu et al., 2010), mostly as a result of limited soil volumes and compacted soils for pavement load-bearing (Grabosky and Gilman, 2004; Day and Amateis, 2011; Sanders et al., 2013), and thus limit ecosystem service provision by trees. In these paved environments, tree pits may be the only uncovered soil surface available for direct water infiltration and evaporation.

Tree pits have traditionally been left uncovered, or in some places covered with decorative iron grates that are suspended above the soil surface and have little influence on water movement. In an effort to maximize the surface available for pedestrian use, municipalities are using permeable pavements to cover tree pits, thus leveling them with the surrounding pavement, which helps minimize the potential of pedestrian tripping hazards. These permeable pavements have been installed under the assumption of not being detrimental to tree growth because of their permeable characteristics. However, there is little research on the impact of this practice on tree growth, especially during tree establishment after transplant.

1.2.2 Impervious surfaces and stormwater runoff problems

Urbanization will keep on increasing in the future (Seto et al., 2012) changing land use and modifying hydrological cycles (Grimm et al., 2008). This urbanization process results in increased stormwater runoff due to soil surface sealing by impermeable pavements, which limit precipitation infiltration into the soil (Scalenghe and Marsan, 2009). The altered hydrologic cycle results in increased water volumes and peak flows in streams during storm events (Dunne and Leopold, 1978), and leads to higher pollutant presence in urban streams (Mallin et al., 2009), driving policy in regards to water management (Walsh et al., 2012). However, there are social, economic, institutional, and governance constraints to applying stormwater control measures (Walsh et al., 2016), resulting in a wide variety of approaches. Urban land and water are typically managed to support healthy streams by applying stormwater control measures (SCMs), which can result in improved water supply, flood mitigation, protection of terrestrial biodiversity, urban cooling, increased resilience to climate change, and human wellbeing (Walsh et al., 2016). These SCMs often are green infrastructure (Eaton, 2018; Hopkins et al., 2018), comprising low impact development (LID) practices that can retain large volumes of runoff and pollutants (Dietz, 2007), and urban forests play a major role in their functioning (Ellis, 2013). Although centralized SCMs, for example detention basins, perform better under larger storm events, and have traditionally been used for stormwater mitigation, they may not be able to manage larger stormwater runoff volumes under climate change rainfall events (Thakali et al., 2017). Tree pits can function as conduits for water infiltration into the soil, as well as for tree water extraction from the soil into the atmosphere. Therefore, they may function as distributed SCMs, which can reduce runoff and improve water quality during small rain events (Hopkins et al., 2017), complementing the role of centralized SCMs.

1.2.3 Permeable pavements and stormwater

Permeable pavements are considered low impact development (LID) practices and are used in urban areas regardless of the presence of vegetation to reduce runoff peaks and volume (Booth and Leavitt, 1999; Brattebo and Booth, 2003; Dreelin et al., 2006; Gilbert and Clausen, 2006; Collins et al., 2008; Rodríguez-Rojas et al., 2018), and to increase infiltration, water quality and groundwater recharge (Hunt et al., 2010; Ahiablame et al., 2012; Mullaney and Lucke, 2014; Weiss et al., 2017). However, permeable pavement stormwater runoff mitigation is also affected by antecedent soil moisture conditions (Castillo et al., 2003; Pitt et al., 2008; Penna et al., 2011), which influence the ratio between surface water runoff and water infiltration into the soil (Castillo et al., 2003).

Nonetheless, many studies demonstrate the stormwater runoff control potential of permeable pavements. For example, a study in the Seattle area, Washington, USA with different types of permeable pavements in parking lots resulted in reduced storm water runoff volume and peak discharges, with a maximum surface runoff of 3% of total precipitation for the largest rainfall event (Brattebo and Booth, 2003). Another study in Georgia, USA, under small rain events (0.3 to 18.5 mm) following dry conditions, showed that a parking lot with grass pavers (pavers with hollow centers that allow grass or other low vegetation to grow interspersed with the pavement) generated 93% less runoff than a conventional asphalt lot (Dreelin et al., 2006). Other studies found that when comparing conventional asphalt with permeable pavers, the latter provided 72% runoff reduction for a median storm intensity of 31.5 mm (Gilbert and Clausen, 2006), and four different types of permeable pavements compared with conventional impermeable asphalt, showed a 95% runoff reduction during storms with a mean precipitation of 20.6 mm (Collins et al., 2008). In regards to water quality, permeable pavements can reduce pollutants transported in water by 85-90% (Legret and Colandini, 1999), thus helping improve runoff water quality (Scholz and Grabowiecki, 2006).

Despite the potential stormwater runoff control benefits of permeable pavements, clogging is a concern in permeable pavement management because of the presumed reduction in infiltration rates over time. For example, a study in the Chicago, Illinois, USA area found infiltration rates decreased between 60-90% after 4 years in parking lots with permeable asphalt, permeable concrete, and pavers, with a 12 inch sub-base with 1-inch aggregates. However, these infiltration rates were still 380 times higher than the rainfall intensity of the majority of the precipitation events in the area. Similarly, Brown and Borst (2014) found in a three-year study of different permeable pavements in a parking lot in New Jersey, USA, that clogging did not significantly reduce infiltration rates.

1.2.4 Pavements and soil moisture and temperature

Distillation caused by pavement cooling and reduced evaporation can result in increased soil moisture in the soil directly under the pavement (Morgenroth and Buchan, 2009; Morgenroth et al., 2013; Fini et al., 2017). A study in New Zealand showed soil moisture to be higher directly under both permeable and impermeable pavements in a sandy loam (Morgenroth and Buchan, 2009). Also, a study in Italy with different types of permeable and impermeable pavements found increased soil water content in soil under impermeable and permeable pavers compared to soil under porous-permeable pavement, and bare soil (Fini et al., 2017). However, in Texas, USA, soil water content in a clay soil in the first 25 cm of soil was not significantly different for a variety of surface treatments, including permeable concrete, impermeable concrete, and bare soil (Volder et al., 2009), probably as a result of root-zone water uptake by mature trees in the experiment.

Permeable pavements allow for increased water evaporation compared with impermeable pavements (Starke et al., 2010), but there are differences in the evaporation rate among permeable pavement types. Brown and Borst (2015) found that there was more cumulative evaporation from permeable concrete (6.5-7.6% of total rainfall volume) than from permeable interlocking concrete pavers (3.9–5.8% of total rainfall volume) and porous asphalt (2.4-5.6% of total rainfall volume). A study in California, USA using permeable asphalt, permeable concrete, gravel, sand and water placed in cylinders for free evaporation, showed that, except for sand, increasing void space in each material also increased evaporation rates (Li et al., 2014). Sand showed no difference in evaporation rates compared to water.

Permeable pavements can be as hot or hotter than impermeable ones (Asaeda and Ca, 2000). However, permeable pavements have been shown to store less heat (Kevern et al., 2012) and can cool down faster than impermeable pavements (Kevern et al., 2012). Evaporation of water through the permeable pavement may be the key to cooler temperatures (Santamouris, 2013). When ample moisture is available to evaporate through the pavement, permeable pavements can maximize their role as a cool pavement (Qin and Hiller, 2016). Therefore, permeable pavements may be a cool pavement only in humid areas where there is no disruption of the water supply to the pavement. Also, soil temperature differences among impermeable, permeable and bare soil may be a result of differences in pavement albedo (Fini et al., 2017).

1.2.5 Urban trees, stormwater management and tree pits

Stormwater runoff management increasingly depends on green infrastructure (Eaton, 2018; Hopkins et al., 2018). Urban trees optimize performance of green infrastructure as a stormwater control tool (McPherson et al., 2005; Ellis, 2013) because they intercept precipitation (Xiao and McPherson, 2002, 2016), remove water from the soil through transpiration, and facilitate water infiltration (Berland et al., 2017). In a greenhouse study, roots of black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L.) penetrated compacted soil and increased infiltration by an average of 153%. *Fraxinus pennsylvanica* Marsh. roots in structural soil grew through the geotextile that separated the structural soil from a sub-base of compacted clay loam, increasing infiltration rates by 27-fold compared with unplanted treatments (Bartens et al., 2008). Although municipalities increasingly rely more on urban trees for stormwater mitigation (Fitzgerald and Laufer, 2017), below ground hydrologic processes are not well quantified (Berland et al., 2017), especially root water uptake and tree transpiration.

Tree pit design is the most important factor influencing the stormwater management performance of street trees. Guarded tree pits had higher infiltration rates than pits with no guard (Elliott et al., 2018), probably as a consequence of less compaction. However, in the case of raised guards over the adjacent pavement, the stormwater performance of these tree pits is limited because surface runoff cannot enter the pits. A rainfall simulation and infiltration experiment in New York City and Philadelphia, USA also found that tree pits without guards had lower infiltration rates that those with guards, and vegetated permeable surfaces generally had lower infiltration rates than engineered permeable surfaces. (Alizadehtazi et al., 2016). However, no characterization of the underlying materials for the different designs was provided.

1.2.6 Tree transpiration and the urban water balance

The urban forest uses a vast amount of water through transpiration. Pataki et al. (2011) in California reported *Platanus ×acerifolia* (60 cm dbh) transpiration of about 177 kg $tree^{-1}$ day^{-1}. Montague et al. (2004) in Utah reported a daily water loss of 2.7 mm (4.4 liters) and a crop coefficient (Kc) of 0.52 for trees of 81.7 cm^2 trunk and 2.9 m height. A study in the Netherlands with sapflow measurements estimated that urban forests transpire 26% of the total rainfall over the growing season, accounting only for the period when leaves are fully expanded (Jacobs et al., 2015). Also, tree transpiration can reduce water outputs in bioretention systems. For example, in a bioretention system in a parking lot in Illinois, USA, modelling showed that tree transpiration accounted for 46-75% of the total water outputs in those systems (Scharenbroch et al., 2016).

Several factors affect the transpiration rate of trees. In a study in California, USA (McCarthy and Pataki, 2010) found greater daily sap flux for *Pinus canariensis* C.Sm. ex DC. in an irrigated site compared with an unirrigated site. In Beijing, China, a study with *Aesculus chinensis* Bunge found that leaf area index (LAI) is the most important factor affecting tree transpiration rates, being positively related (Wang et al., 2012). Furthermore, transpiration rates can be affected by the environment around the tree. For example, Kjelgren and Clark (1993) in Seattle, Washington, USA, found lower stomatal conductance and leaf area for *Liquidambar styraciflua* L. at a plaza site compared with a nearby park, probably due to better growing conditions for trees at the park site. Also, in a greenhouse study with *Acer rubrum* L., Fair et al. (2012) found that higher soil bulk density (1.77 $Mg \cdot m^{-3}$compared with 1.64 $Mg \cdot m^{-3}$) reduced tree transpiration by 70-80%, probably due to less water availability in the compacted treatment. A study in Italy found that impermeable asphalt reduced transpiration in *Fraxinus ornus* L. compared with bare soil, pavers, and porous pavement treatments (Fini et al., 2017), possibly as a result of a pavement-induced higher soil temperature. However, we need to further understand tree transpiration from base course storage (Kuehler et al., 2017) as well as quantify the overall impact of trees on the tree pit system to fully assess the effect of trees on the urban water balance.

Tree species differ in transpiration rates. In general, *Platanus* species are known to have high transpiration rates and poor stomatal control. In a study in Utah, USA, Bush et al. (2008), found *Platanus* ×*acerifolia* (Aiton) Willd. to have poor stomatal control. Also, McCarthy and Pataki (2010) found this same tree taxon was unresponsive to shallow soil moisture in terms of daily sap flux. A study in Germany found *Platanus* ×*hispanica* to have higher water use efficiency than four other common urban deciduous trees, even under high vapor pressure deficit, and despite having higher transpiration rates (Gillner et al., 2015).

1.2.7 Pavements and tree growth

Pavement installation alters soil properties (such as density) and processes (such as infiltration and evaporation), which can limit tree growth (Jim, 2001) and impair tree health (Savi et al., 2015). As a consequence, it is believed that pavements have effects on trees that result in decreased growth, premature decline, and death (Kjelgren and Clark, 1994; Iakovoglou et al., 2001; Schröder, 2008).

On the other hand, permeable pavements are typically perceived as infrastructure that enhances tree growth and survival through increased water infiltration and soil aeration (Tennis et al., 2004; Ferguson, 2005; Mullaney et al., 2015b), compared to conventional impermeable pavements. Permeable pavements have been tested for their contribution to improved water movement into the soil, and thus potentially promote tree growth compared to impermeable pavements (Volder et al., 2009), although tree growth benefits derived from permeable pavement installation has not been demonstrated. For example, in a study in Italy, Fini et al. (2017) also found increased soil water content under permeable and impermeable pavement at 20-cm depth compared with bare soil, but above-ground growth of *Celtis australis* L. and *Fraxinus ornus* L. trees seemed unaffected. Overall, the impact of permeable pavements on the surrounding environment is not well understood (Morgenroth and Buchan, 2009). To date, there is little research on the effects of paving on tree growth and physiology (Morgenroth and Buchan, 2009; Volder et al., 2009; Morgenroth, 2011; Viswanathan et al., 2011; Weltecke and Gaertig, 2012; Savi et al., 2015).

Both installation practices and tree life stage are important factors of tree growth response to pavements. For example, a study by Rahman et al. (2013) found that the tree pit treatment with pavers that had a gravel base course and was supplied with irrigation reduced the growth rate of *Pyrus calleryana* Decne. compared to the tree pit treatment of mulch and no supplemental irrigation. The reduced growth rate was possibly due to soil compaction during the installation of the pavers. Mullaney et al. (2015a) found the above-ground growth of *Melaleuca quinquenervia* (Cav.) S.T. Blake to be positively affected when pavement over clay soil included a gravel base course, but in sandy soil this positive effect on tree growth only occurred without the gravel. In another experiment in Texas, USA, there was no difference in growth rate, leaf water potential or leaf gas exchange among mature *Liquidambar styraciflua* L. under various surface treatments including permeable concrete, impermeable concrete (both without a gravel base), and bare soil, over a two-year time period (Volder et al., 2009).

1.2.8 Pavements and tree root growth and distribution

The generally negative effect of pavement on tree growth is likely a consequence of physical or chemical impediments that restrict root systems (Day et al., 2010b). Regardless of soil cover, tree roots may grow closer to the soil surface (Crow, 2005; Wang et al., 2006); however, it is the combination of soil compaction, texture, soil moisture regime, and tree species that ultimately affects tree rooting depth (Day et al., 2010a). Therefore, pavements affect root growth distribution by changing soil temperature, water content, and other properties of the soil underneath the pavement. For example, very high soil temperatures impede or halt root growth (Kaspar and Bland, 1992; Harris et al., 1995). Considering that optimal temperatures for root growth for most temperate tree species are less than 30 ºC (Graves, 1994), the soil temperature of more than 40 ºC found under asphalt in a study in Arizona, USA, (Celestian and Martin, 2004) shows the potentially negative effects of pavement on root growth due to high soil temperatures. Another study in Illinois, USA, by Kjelgren and Montague (1998) showed soil temperature under asphalt to be 20-25 ºC higher than for turfed areas.

The soil compaction necessary to install pavements, and the increase in soil water content directly under pavement (Morgenroth and Buchan, 2009; Morgenroth et al., 2013) can encourage a shallower tree root development (Lemaire and Rossignol, 1997; Randrup et al., 2001; Morgenroth, 2011), leading to pavement disruption by tree roots in sidewalks, with high maintenance costs in urban areas (Randrup et al., 2001). Permeable pavements, however, have not been found to alter root depth distribution any differently than impermeable ones (Morgenroth, 2011), although some studies suggest they might lead to less conflicts between trees and pavements (Mullaney and Lucke, 2014).

Combined soil and pavement effects may influence root production. For example the absence of a base course under the pavement (both permeable and impermeable) reduced root length production and root life span in a study in Texas, USA (Volder et al., 2014). Morgenroth (2011) found more root biomass after two growing seasons for *Platanus orientalis* L. under porous pavement without a compacted subgrade or gravel base than under impermeable pavement. However, when treatment included a gravel base and compacted subgrade, root biomass was similar to that of trees in bare soil (Morgenroth, 2011). Also, the combination of structural soils and pavement can promote root development and tree growth (Day et al., 2008).

1.2.9 Base course effects under permeable pavements

The physical characteristics and construction and installation setup of the gravel and soil layers beneath pavements condition water movement in the soil. For example, several studies have shown that the interaction of a base course and site-specific characteristics, mainly soil and climate, modify soil water content throughout the soil profile (Morgenroth et al., 2013; Mullaney et al., 2015a). These studies found that soil water content under pavement was not as high when a gravel base course was installed under the pavement (Morgenroth et al., 2013). Comparable results were found in an Australian experiment with clay soils, while a gravel base course increased soil water content near the surface in sandy soils (Mullaney et al., 2015a). Also, the particle size of the base course has a strong influence on infiltration, drainage, and water storage (Andersen et al., 1999), as it does the base thickness (Fassman and Blackbourn, 2010; Winston et al., 2018). For example, a base with a fine aggregate had a higher evaporation rate compared with coarser base aggregates, but also had less drainage and more water retention (Andersen et al., 1999). In New Zealand a study with permeable pavers and a deep base course (48 cm) over two years produced discharge comparable to pre-development conditions, despite the low permeability of the underlying soil and the steep slope of the terrain (Fassman and Blackbourn, 2010). A study in Ohio, USA, in a parking lot with pavers over low permeability soils, drainage into the soil was the dominating factor for discharge volume reduction, supporting the effectiveness of permeable pavements even over low permeability soils. A 15-cm water storage zone was a major contributor to volume reduction through drainage and evaporation (Winston et al., 2018), pointing to the importance of the base course characteristics for optimal performance, and to the need for further investigation, especially in regards to design (Weiss et al., 2017).

1.3.0 Water flow modeling

Modeling has become an important part of ecological research, and has been used in many fields ranging from invasive species spatial spread (Peterson, 2003) to climate change scenarios (Sperry and Love, 2015). More specifically, modeling has been used in urban ecology to show the benefits of the urban trees, such as carbon sequestration (Aguaron and McPherson, 2012), to help policy makers and urban foresters make informed decisions, for example, predicting tree growth (McPherson and Peper, 2012), or showing environmental challenges in urban areas, as in the extent of soil sealing in cities (Scalenghe and Marsan, 2009).

Hydrological processes are also of importance to ecologists, and many different computer tools have been developed to predict soil water flow and transport processes in natural subsurface systems (Šimůnek and de Vos, 1999; Šimůnek et al., 2008). Some examples include the Storm Water Management Model (SWMM), Soil and Water Assessment Tool (SWAT), and Global Multilevel Coordinate Search algorithm combined with the Nelder-Mead Simplex algorithm (GMCS-NMS). SWMM was used for modeling water runoff in urban areas (Gironás et al., 2010), although Zhang and Guo (2015) found limitations to its use. SWAT has been used for large scale hydrological modeling of water and nonpoint source pollutants management testing (Arnold et al., 1998). The GMCS-NMS algorithm has been used for inverse modeling to find out hydraulic properties of saturated soils (Lambot et al., 2002), and soil hydraulic properties in fruit crop systems in the Canary Islands (Ritter et al., 2003). GIS and remote sensing have also been tools for addressing hydrological issues (Weng, 2001).

Modeling is commonly used to understand hydrological process in soils, such as predicting water fluxes and root water uptake (Clausnitzer and Hopmans, 1994; Wu et al., 1999; Tron et al., 2015), groundwater recharge (Aravena and Dussaillant, 2009), or solute transport (Loague and Green, 1991). Although limited, recently hydrological modeling has also been done to understand hydraulic behavior of permeable pavements. Qin and Hiller (2016) found that the evaporation rate of pervious concrete was determined by water near the surface, limiting the choice of pervious concrete as a cool pavement. Zhang and Guo (2015) modeled permeable pavement water runoff reduction due to increased water, but model accuracy was low when pavement thickness was less than 12 cm. Further research with water modeling is needed to better understand the hydraulic properties of permeable pavements, and their impact on hydrological processes.

1.3.1 HYDRUS modeling

HYDRUS is another water movement modeling tool that numerically solves Richard's Equation to simulate both saturated and unsaturated water flow in porous media. When used in combination with field observations it can provide valuable estimations of water movement in the soil in different scenarios (Newcomer et al., 2014). HYDRUS not only models water flow through layered soils, but also includes water withdrawal by roots (Wu et al., 1999). These data can then be used to estimate soil water status at every depth in the profile under different climate scenarios, allowing results to be used in many settings and situations.

HYDRUS has been used in many fields. In agriculture, for example, it has been applied to predict soil water content in irrigated cotton fields (Bufon et al., 2012), for modeling water and solute fluxes in crop fields (Haws et al., 2005), and to simulate water flow of melon and lettuce irrigated fields to estimate groundwater recharge (Jiménez-Martínez et al., 2009). Ecological studies have also found applicability to HYDRUS modeling such as water runoff estimation from green roofs (Hilten et al., 2008), to construct a water balance in an ecologically sensitive habitat in South Africa (Jovanovic et al., 2013), and to estimate the hydraulic properties of a filter in a wetland (Morvannou et al., 2013).

Several studies have used HYDRUS as a tool to understand water flow through permeable pavements (Illgen et al., 2007; Carbone et al., 2014). The Carbone et al. (2014) study used HYDRUS-1D to better understand preferential flows in permeable pavement, which can be difficult because of the unsaturated nature of water flow through pavements. Illgen et al. (2007) calibrated HYDRUS-2D with experimental field data on a variety of permeable pavement types, in order to simulate different conditions. Another application of HYDRUS-2D was to predict soil water recharge in bioinfiltration sites (Newcomer et al., 2014). A study in Brazil characterized the hydraulic properties of permeable pavements in order to model water runoff and infiltration using HYDRUS-1D (Coutinho et al., 2016), and Brunetti et al. (2016) successfully used HYDRUS-1D in the hydraulic behavior prediction of permeable pavements. However, HYDRUS has never been used to describe soil water fluxes in constructed urban tree pits, despite its potential to estimate soil water content distribution under pavements and thus, make predictions for preferential root growth. These simulations could be used for improved tree pit / pavement design to reduce tree-infrastructure conflicts, and to manage stormwater.

1.3.2 Research objectives

To better understand the influence of permeable pavements on tree growth and root distribution, and on the tree pit water balance, we developed a series of research objectives for this experiment:

1. Evaluate the influence of porous pavement on tree growth and development during establishment.
2. Assess the role of porous pavement in altering the depth and emergence of roots of establishing trees.
3. Distinguish above- and below-ground responses to porous pavements mediated by soil water content and temperature.
4. Construct a water balance for a model tree pit system.
5. Quantify changes in water balance attributable to the presence of trees and to permeable pavements.
6. Consider implications for urban stormwater management strategies.
7. Use empirical data to calibrate and validate HYDRUS-1D.
8. Assess HYDRUS-1D suitability as a tool to understand soil water behavior under permeable pavements in urban tree pits.
9. Use simulations of soil water content in constructed soil profiles under different permeable pavement thicknesses and root depth distributions to investigate the potential of HYDRUS-1D as a tool to inform engineers on pavement design and tree integration in urban landscapes.

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Chapter 2

Porous-Permeable Pavements Promote Growth and Establishment and Modify Root Depth Distribution of *Platanus ×acerifolia* (Aiton) Willd. in Simulated Urban Tree Pits

Reprinted from Urban Forestry & Urban Greening, Vol 33, 27-36, Francisco Javier de la Mota Daniel, Susan D. Day, James S. Owen, Ryan D. Stewart, Meredith K. Steele, Venkataramana Sridhar, Porous-permeable pavements promote growth and establishment and modify root depth distribution of *Platanus* × *acerifolia* (Aiton) Willd. in simulated urban tree pits, Copyright (2018), with permission from Elsevier.

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.

Keywords: London plane; street tree; pervious pavement; resin-bound gravel; soil temperature; SuDS

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 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 ºC (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 quinquenervi*a (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 ºC, 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. 2.1). 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 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 $g \cdot m^{-2}$, 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-liter batches with 500 ml of Gravel-Lok™ (Cell Tek LLC., Crofton, MD, USA), a polyurethane binder (Fig. 2.1).

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-hour intervals (Model CR1000 Campbell Scientific, Inc., Logan, UT, USA) between July and December 2015. After

January 2016, data were logged every 15 minutes. 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. 2.2). 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. 2.2). 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. 2.4 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. 2.2. See Fig. 2.4 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. 2.2. See Coastal Plain in Fig. 2.4 for July and August 2016 statistics).

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. 2.3, Table 2.1 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. 2.4). 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. 2.4). 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. 2.4, on July 23, 2015). In the Coastal Plain this pattern is not as clear. By the end of the experiment, root presence 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. 2.4). 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. 2.5). 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. 2.5), although 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. 2.5), 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. 2.2). 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 ºC 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 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 2.1). 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. 2.6, 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. 2.6), 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 2.1 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. 2.6) 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. 2.6 and Table 2.1). 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. 2.6). 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 2.1). 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 2.1).

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. 2.2). 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. 2.4), 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 ºC, 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 ºC 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 ºC) 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. 2.6). 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.

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Figures and Tables

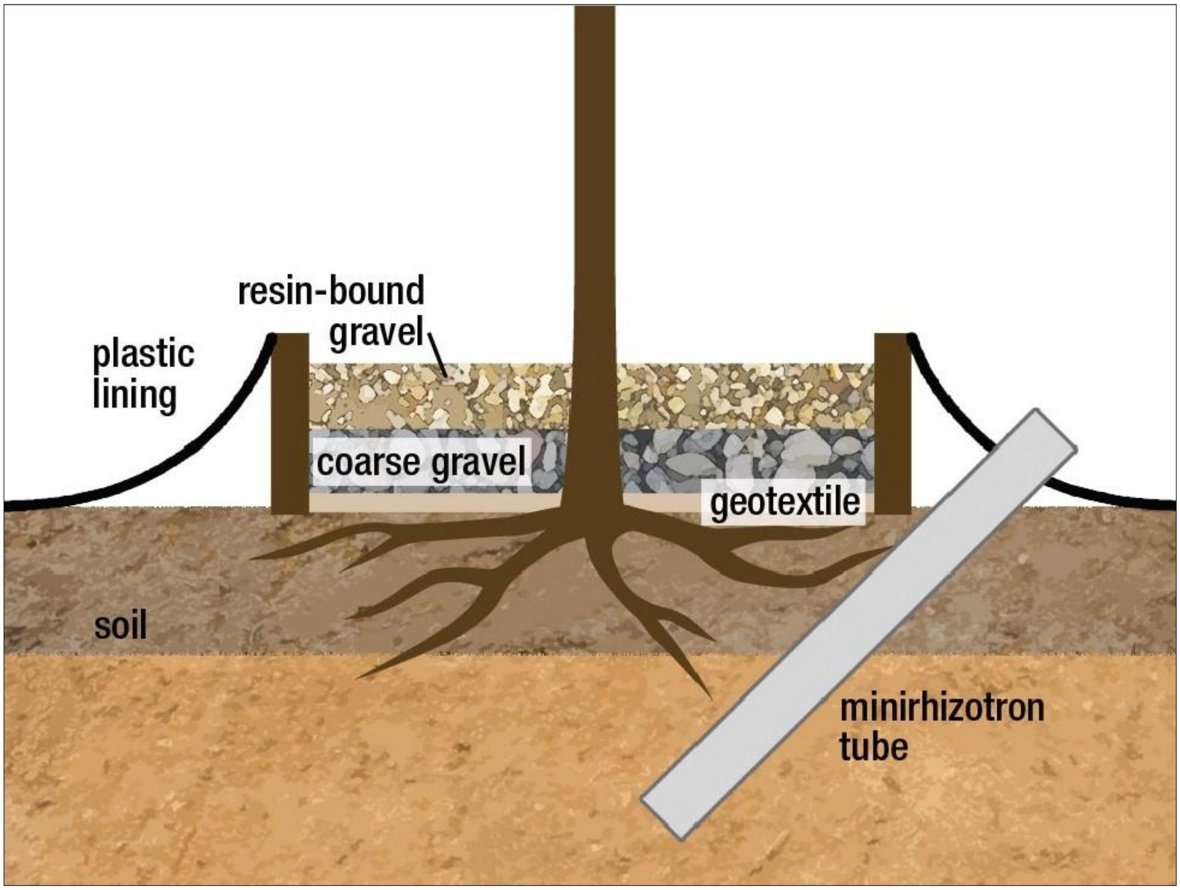

Fig. 2.1. Tree pit vertical section from porous pavement treatment (PP) showing arrangement of geotextile, gravel base course, and porous pavement as well as minirhizotron location and attachment of plastic sheeting to exclude surface runoff (not to scale). Image by Sarah Gugercin.

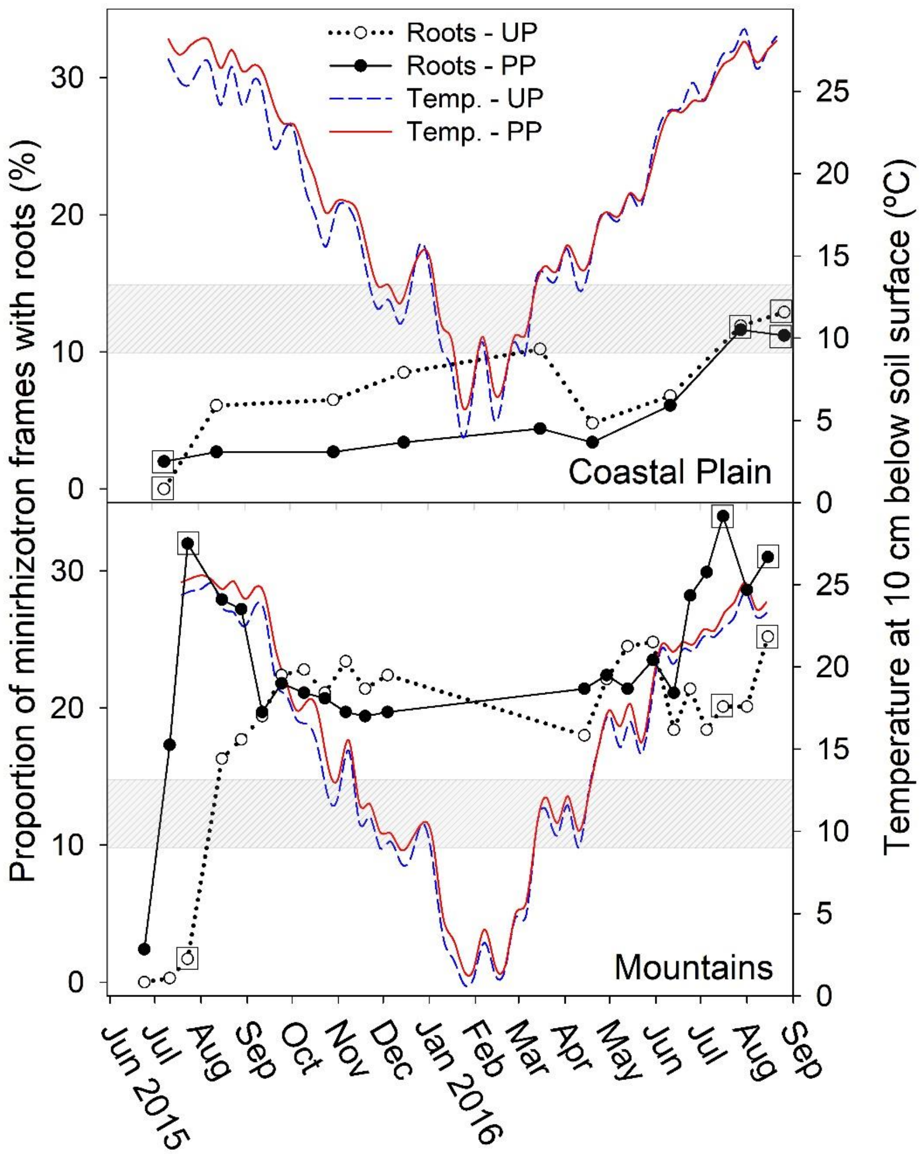

Fig. 2.2. Soil temperature and change over time in the proportion of all minirhizotron frames (294 per treatment) that had visible roots over the first two growing seasons after planting at two experiment locations. Soil temperature is displayed as a weekly average (n=1). Shaded area shows estimated 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. 2.4.

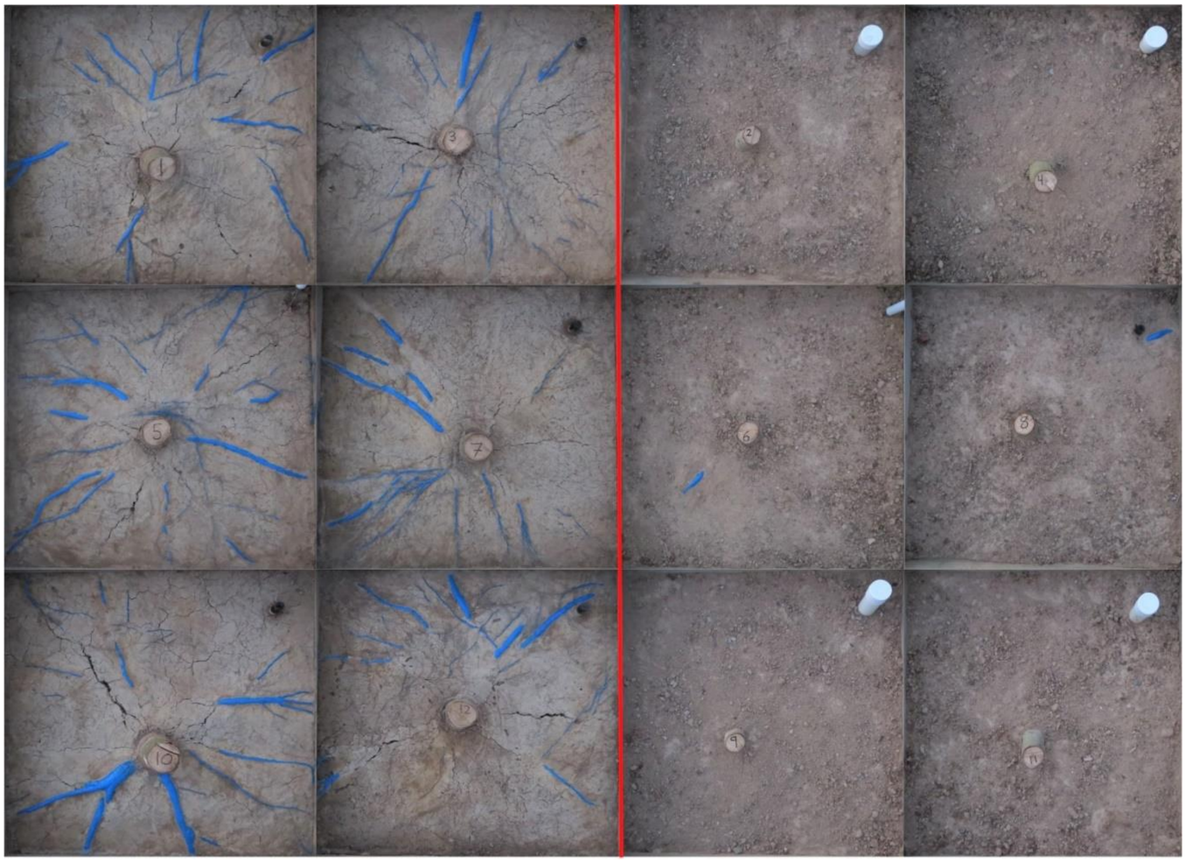

Fig. 2.3. Photographs of surface roots (painted blue) of *Platanus ×acerifolia* ‘Bloodgood’ trees in tree pits with porous pavement (PP) after pavement removal (left, first two columns) and unpaved tree pits (UP, at right), at the Mountains site at the end of the experiment.

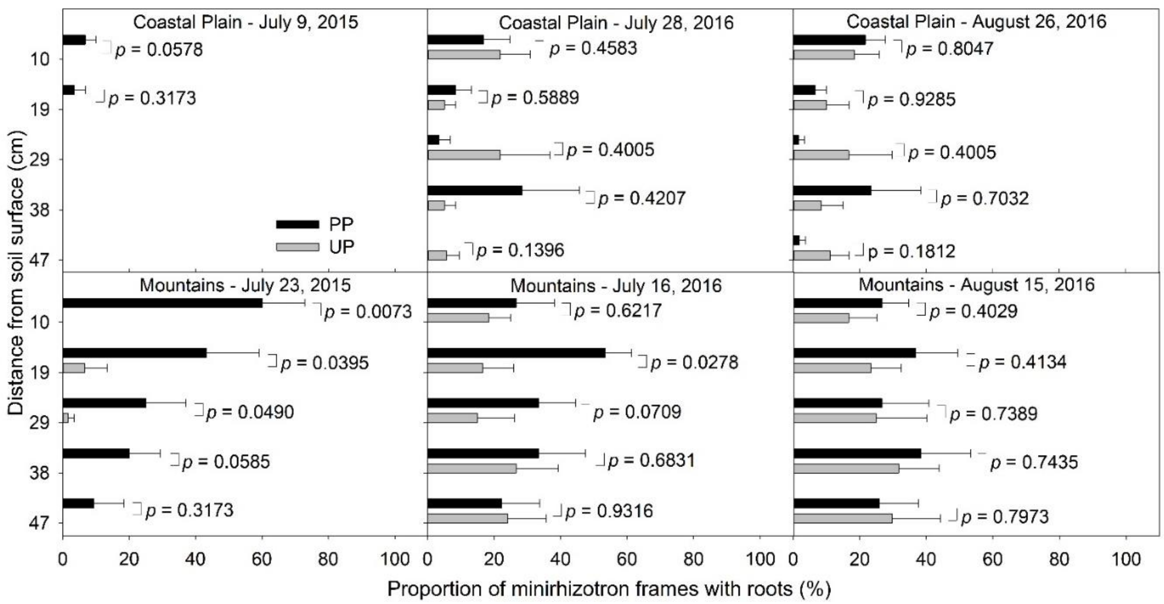

Fig. 2.4. Proportion of minirhizotron frames with roots visible at selected time periods at 5 soil depths, for *Platanus ×acerifolia* ‘Bloodgood’ planted in simulated tree pits with porous pavement (PP) and bare soil treatments (UP), at two locations. Periods illustrated include: initial root appearance (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. 2.2. 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).

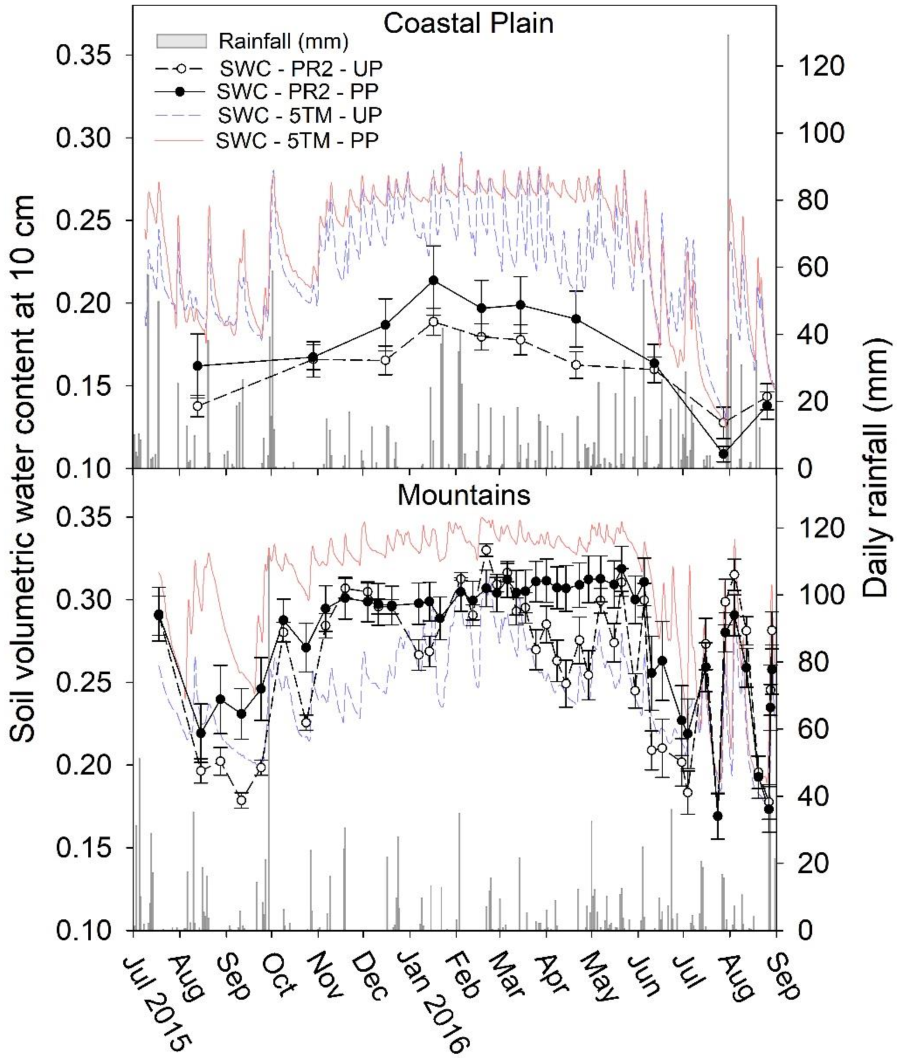

Fig. 2.5. Change in soil volumetric water content at 10 cm below soil surface for simulated tree pits (1 m2 each) planted with Platanus ×acerifolia ‘Bloodgood’, with porous pavement (PP) and bare soil treatments (UP), at two experiment locations. 5TM lines represent daily average soil volumetric water 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.

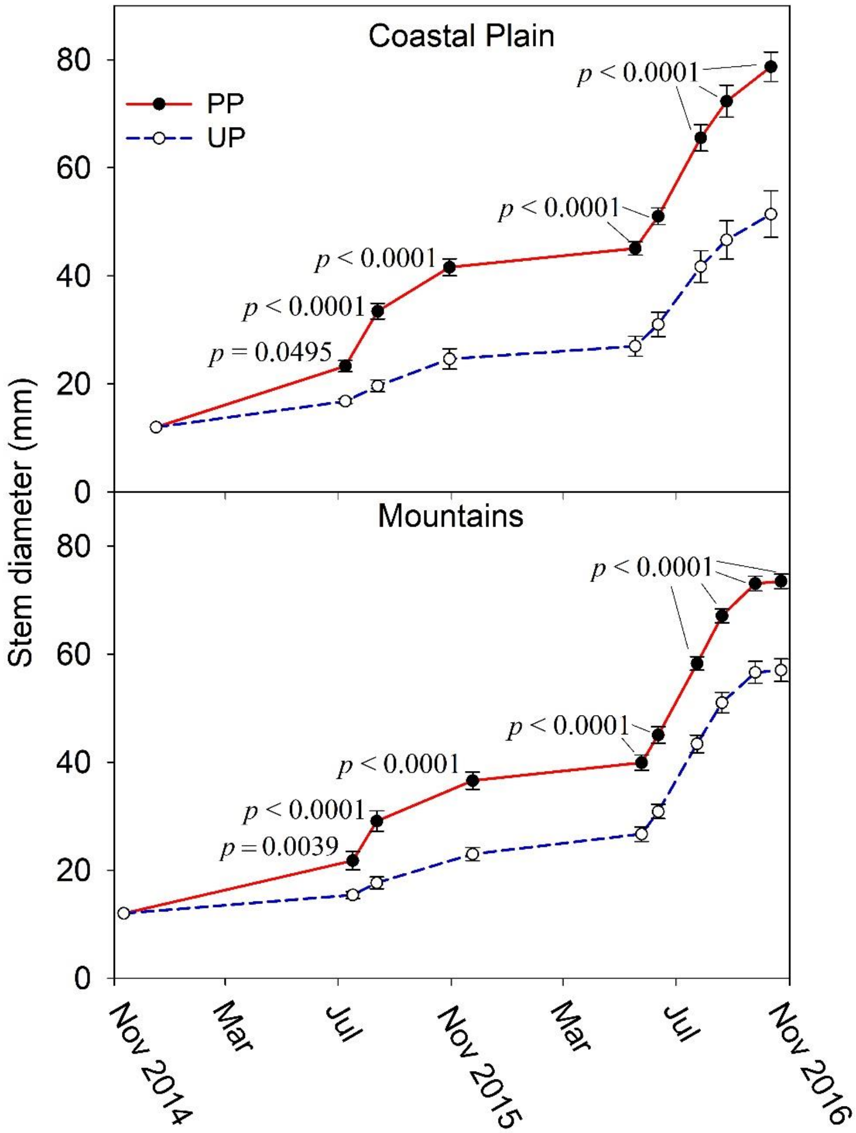

Fig. 2.6. Change in stem diameter measured at 152 mm above soil surface, of *Platanus ×acerifolia* 'Bloodgood' trees planted in simulated tree pits with porous pavement (PP) and bare soil treatments (UP), at two experiment locations, during the first two growing seasons after planting. Error bars represent the standard errors of the means (n=6 in Mountains, n=5 in Coastal Plain).

Table 2.1. 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).

Chapter 3

A water balance approach to assessing street trees and permeable pavements—where does the water go?

Abstract

In city streets, trees often grow in pavement cutouts (tree pits), which can be the only non-sealed surfaces within the streetscape. Urban tree pits therefore may act as important conduits for water exchange between soils and the atmosphere in otherwise impervious environments. This exchange is of particular interest for stormwater management, since tree pits have the potential to retain and store stormwater, thus serving as distributed stormwater control measures. Still, there is not sufficient data available to assess the effect of permeable tree pits on the urban water cycle. To address this gap, we quantified how the water balance of tree pits varies with the presence of trees and permeable pavement covers. We performed a completely randomized experiment with two factors: paved with porous pavement versus unpaved, and planted with *Platanus* ×*acerifolia* 'Bloodgood' versus unplanted (n = 6). We measured tree sap flow over one week in June 2017 and monitored soil water content and weather variables during this week and throughout the course of the 2-year experiment. In 2017, tree transpiration was 33% of water outputs for unpaved and planted pits, and 64% for paved and planted pits. In one week in June 2016, planted pits had decreased root-zone water storage, while unplanted pits showed increased storage. To mimic a streetscape and explicitly incorporate the effects of roots beneath impervious surface, we also developed a water balance for the entire study area in 2017. This analysis indicated water loss in all pits, with transpiration becoming the dominant factor in the water balance during leaf-on periods. Both at the tree pit and streetscape scale, transpiration was more than 100% of water inputs. Increasing bare soil tree pit size and converting adjacent impermeable pavement to permeable pavement may increase infiltration, evaporation, and tree size results, improving stormwater management efforts. Our findings show that regardless of soil cover, trees may improve urban stormwater retention by increasing urban system capacitance through transpiration.

Keywords: Tree transpiration, porous pavement, stormwater management, sap flow, soil water storage, distributed stormwater control measures, green infrastructure, tree pits

1. Introduction

Urbanization is expected to continue to increase (Seto et al., 2012) and this change in land use and cover alters hydrological cycles (Grimm et al., 2008), increasing stormwater runoff and requiring new water resource management strategies in cities (Walsh et al., 2012). Runoff mitigation practices increasingly rely on green infrastructure (Eaton, 2018; Hopkins et al., 2018), of which urban forests and green spaces are essential components (Ellis, 2013). Urban trees are valuable tools that contribute to this green infrastructure. But even as many cities employ stormwater credit systems to increase tree planting (Cappiella et al., 2016), there is uncertainty in quantifying tree performance for stormwater mitigation (Berland et al., 2017), especially in regards to partitioning precipitation into runoff and below-ground hydrologic processes such as infiltration, groundwater recharge, water extraction via root uptake and transpiration.

In dense urban areas trees often grow in openings in the pavement (tree pits), which may be the only unpaved surface in these very intensely urbanized sites. Thus, tree pits can serve as retention structures for surface runoff, albeit temporarily, and become important conduits for water into the soil, and from the soil to the atmosphere, whereas adjacent impervious surfaces restrict infiltration and evaporation. As such, tree pits could be considered part of decentralized or distributed stormwater control measures, which reduce runoff and improve water quality (Fletcher et al., 2015). Traditionally stormwater mitigation infrastructure has relied on centralized measures (e.g., large swales and detention basins), which are often insufficient to manage stormwater runoff under extreme climate change storm events (Thakali et al., 2017). As cities pursue multiple avenues for decentralized stormwater management, tree pits may potentially play a valuable role when pervious surfaces are limited.

Tree pits have a variety of surface covers that may differentially influence their hydrologic behavior. Permeable pavement is increasingly being used around trees, especially in tree pits. While permeable pavements alter water and tree root distribution (Morgenroth and

Buchan, 2009; Morgenroth and Visser, 2011; de la Mota Daniel et al., 2018), their overall effects on the water balance of tree-pavement systems are unknown. In addition, permeable pavements are considered low impact development (LID) practices and are used in urban areas to reduce runoff peaks and volume (Booth and Leavitt, 1999; Brattebo and Booth, 2003; Dreelin et al., 2006; Gilbert and Clausen, 2006; Collins et al., 2008; Rodríguez-Rojas et al., 2018), increase infiltration, improve groundwater recharge, and to protect water quality (Hunt et al., 2010; Ahiablame et al., 2012; Mullaney and Lucke, 2014; Weiss et al., 2017). Permeable pavements also allow increased soil water evaporation compared with impermeable pavements (Starke et al., 2010) and can increase stormwater storage and soil moisture (Mullaney and Lucke, 2014). However, the influence of permeable pavement on the urban water cycle is not well understood, especially in terms of its interaction with trees and potential effects on tree transpiration (Fini et al., 2017).

Many studies of urban trees and tree pits focus on select components of the system. For example, Elliott et al. (2018) examined the effect of tree pit cover on infiltration, while other studies have investigated the soil water and physiological implications of permeable pavements around trees (Volder et al., 2009; Morgenroth and Visser, 2011; Mullaney et al., 2015a; Fini et al., 2017; de la Mota Daniel et al., 2018). Although several studies examine transpiration rates of urban trees (Pataki et al., 2011; Gillner et al., 2015; Gotsch et al., 2018), only some have been explicitly linked to below-ground and pavement conditions (Kjelgren and Montague, 1998; Gillner et al., 2015). A full accounting of how tree-pavement systems affect hydrologic processes does not, to our knowledge, exist, although some models have been proposed (Vico et al., 2014).

Trees play an important role in the urban water balance (Xiao and McPherson, 2002; Pataki et al., 2011; Jacobs et al., 2015; Livesley et al., 2016; Xiao and McPherson, 2016) and as part of green infrastructure represent important components of the ability of a watershed to retain water, known as watershed capacitance (Miles and Band, 2015). Tree roots can contribute to this capacitance by increasing soil permeability (Bartens et al., 2008) and by reducing water outputs in bioretention systems through transpiration (Scharenbroch et al., 2016). Tree transpiration alters antecedent soil moisture conditions, influencing the ratio between surface water runoff and water infiltration into the soil (Castillo et al., 2003; Pitt et al., 2008; Penna et al., 2011) and soil water storage (Sehgal et al., 2018). However, there is still a knowledge gap in regards to the potential of trees to transpire water from under-pavement storage and thereby influence capacitance of the system (Kuehler et al., 2017). Because tree transpiration can be affected by the amount of pavement around a tree (Kjelgren and Clark, 1993) and by soil moisture distribution (Bartens et al., 2009), an empirically based, integrated analysis of the tree pit system (tree, soil and pavement) water balance is needed to quantify the effect of street trees on the hydrologic processes of individual tree pits and collectively over larger urban spaces.

Green infrastructure relies on water interception, transmission, storage and transpiration as key components of the water balance, partly through trees and permeable pavements. Thus, determining their contributions to the urban water balance will allow cities to most effectively enact stormwater management policies. In this study we explored the role of these tree contributions to urban hydrology, through monitoring plant and environmental factors in simulated urban tree pits. Our objectives were to: 1) construct a water balance for a model tree pit system; 2) quantify changes in water balance attributable to the presence of trees and to permeable pavements; and 3) consider implications for urban stormwater management strategies.

2. Materials & Methods

2.1. Experimental site

The study site was in Blacksburg, Virginia, USA (Lat. 37.218739, Long. 80.463679, Elev. 622 m) in the Valley and Ridge physiographic region. 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. The site soil was a Groseclose-Poplimento soil series complex (fine, mixed, subactive, mesic Ultic Hapludalf). The Ap horizon was 35 cm deep and had a silt loam texture (23% sand, 63% silt, and 14% clay), with a mean bulk density of 1.37 ± 0.01 Mg m^{-3}; the Bt horizon was a silty clay (12% sand, 41% silt, and 47% clay) with a mean bulk density of 1.21 ± 0.03 Mg m^{-3} (± values represent standard errors).

2.2. Experimental design and installation

The experimental site was previously covered by a mixture of herbaceous vegetation (mostly *Lolium perenne* L. and *Trifolium repens* L.). This existing vegetation was killed with glyphosate and removed by manually scraping with a spade, but no soil tilling was performed. Subsequent weed growth was suppressed with glyphosate as needed over the duration of the experiment.

In November 2014 we installed 24 simulated sidewalk cutouts for tree planting (tree pits) with 1 m × 1 m treated wooden frames in a completely randomized full factorial design with two factors: paved or unpaved, and planted with trees or unplanted. This resulted in four treatments: NoTree-Unpaved, NoTree-Paved, Tree-Unpaved, and Tree-Paved. Pavement was porous-permeable resin-bound gravel pavement (porous-permeable pavement - installation described below), and trees were *Platanus ×acerifolia* 'Bloodgood' two-year-old bare-root uniform whips with approximately 1.2-cm diameter stems at 15 cm above ground, produced from rooted cuttings (Carlton Plants LLC Dayton, Oregon, USA). At planting, root systems were pruned to 20 cm × 20 cm × 20 cm, and stems were pruned to 110 cm height.

Tree pits were spaced 1.5 m apart (edge-to-edge). To simulate impermeable pavement between the tree pits we covered all of the ground between tree pits and extending 1 m beyond the plot boundary with 0.254-mm black polyethylene sheeting, and stapled it to the top of the wooden frames, thus excluding all surface water from adjacent areas. The plastic was then covered with a 10-cm thick layer of woodchips to protect the plastic and avoid soil solarization.

Pavement was then installed in the Tree-Paved and NoTree-Paved plots by: 1) laying a sheet of non-woven geotextile (DuPont™ Typar® SF27 90 $g \cdot m^{-2}$, DuPont™ Typar® Geosynthetics, Luxembourg) on the soil surface; 2) placing a 5-cm base course of crushed granite screened to 25-45 mm (Virginia Department of Transportation #57) over the geotextile; and 3) pouring a 5-cm layer of porous-permeable pavement (a mixture of washed pea gravel screened to 9.5 mm, mixed with Gravel-Lok™ (Cell Tek LLC., Crofton, Maryland, USA), a polyurethane binder. Pavement was mixed in batches (20 L pea gravel + 0.50 L resin). A small 10-cm diameter hole was formed in the center of the pavement around the tree to allow for tree stem diameter increase. However, to avoid this hole becoming a preferential path for water infiltration, it was filled with loose pea gravel around the tree stem. No hole was made in NoTree-Paved plots.

2.3. Tree sap flow

All tree sap flow measurements occurred between 10 June 2017 and 18 June 2017. We chose this period for being representative of the tree pit system during the growing season, because trees were fully leafed out. We monitored sap flow on all 12 trees using a heat-balance sap flow system (Flow 32-AO Sap Flow Measurement System, Dynamax, Houston, Texas, USA). We measured tree trunk diameter at different heights per tree to find the optimal location for the sap flow gauges, and fitted one gauge (SGB25-ws, Dynamax, Houston, Texas, USA) around the trunk of each tree. The gauge includes an insulating foam collar, and additional foam collars were added above and below the gauge. Each gauge-collars setup was covered with a reflective heat shield, which also prevented rainfall from entering between the gauge and the tree stem. Tree foliage further protected the gauges from direct sunlight. The gauge model we used accommodates a maximum stem diameter of 32 mm and were located at the lowest possible height on each tree. Thus, for all trees there were branches below the gauges for which sap flow was not recorded, resulting in above- and below-gauge canopy sections. We followed the method of Bartens et al. (2009) to estimate whole-tree sap flow (g h^{-1}) based on above- and below-gauge leaf area for each tree (see below for leaf area methods). Sap flow was calculated every minute, and the average logged every 5 minutes in grams per hour (g h^{-1}). Sap flow was then normalized as a flux for a 1-cm^2 leaf area, and an average flux rate calculated for each day (g h^{-1} cm^{-2}). This flux was then used to calculate total transpiration in grams per day per 1 cm^2 of leaf for each 24-h period. Total transpiration for the entire 7-day period of sap flow monitoring was calculated by summing these daily values.

There were occasional gaps in data recording. However, these occurred in the evenings when sap flow rate was already decreasing and very low, so we interpolated flow rates for those periods for data analysis purposes. Every morning between approximately 5:30 and 7:30 h we observed a very high peak in sap flow rate. This temporary overestimation of sap flow rate is typically an artifact of low early morning flow rates when sap is heating for a long time and then followed by colder sap from the root system (Ham and Heilman, 1990; Weibel and de Vos, 1994; Grime et al., 1995). We filtered these anomalous flow rates by interpolating for those periods (Tarara, 2009). One sap flow gauge in the Tree-Unpaved treatment malfunctioned, and transpiration values for that tree were excluded for 2017 tree pit comparisons. However, for the complete study plot water balance calculations (see Section 3.1 *Water Balance – Plot*), sap flow for that gauge was estimated based on the value from the tree in Tree-Unpaved closest in size.

2.4. Leaf area

Trees were harvested immediately after sap flow measurements were completed, and leaves were stripped from branches, separating the leaves from above and below sap flow gauges. We selected subsamples of leaves from above and below the gauges for three trees in paved tree pits, and three trees in unpaved tree pits. These subsamples consisted of groups of 5, 10, 15, 20, and 25 leaves per canopy section (above and below gauge for each tree). We measured leaf area of each subsample with a Li-3100 Area Meter (Li-Cor Biosciences, Lincoln, Nebraska, USA) and oven dried each subsample at 62 °C to a constant weight. We determined the leaf area/dry weight relationship by linear regression in JMP. Separate regression relationships were created for the above- and below-gauge sections of the canopy to account for the observed different leaf size and morphology in the upper and lower portions of the trees: leaves were typically bigger in the above-gauge section, and also had very large stipules that created additional transpirational surface; the below-gauge section had smaller leaves, often with no or very small stipules. As a result, the linear regression equation for leaf area above the gauge was: $A_{leaf} = 249.51 + 109.46dw$ ($R^2 = 0.947$, $p = <0.0001$), and for below gauge: $A_{leaf} = 96.94 + 153.96dw$ ($R^2 = 0.946$, $p = <0.0001$), where dw is leaf dry weight (g) and A_{leaf} is leaf area (cm^2). All leaves from above and below gauges on all trees were oven dried and weighed, and total leaf area calculated for each above- and below-gauge section of each tree (Bartens 2009). Also, to further characterize tree canopy, at the end of the experiment (18 June 2017) and on 12 June 2016, for comparison between two consecutive years, trunk diameters were measured in two directions (east to west and north to south) at 15 cm above soil surface with microcalipers (Mitutoyo, Kanagawa, Japan) and averaged for each tree. Canopy width was measured with a measuring pole at the conclusion of the experiment (June 2017).

2.5. Soil water monitoring

We monitored soil water content at one replicate from each of the four treatments by installing Decagon 5TM capacitance soil sensors (Decagon Devices, Inc., Pullman, Washington, USA) at 10-, 30- and 60-cm depths. Data were logged every 15 minutes (Model CR1000, Campbell Scientific, Inc., Logan, Utah, USA). 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 20 tree pits, and at four locations in the center of the plot under the plastic covering (and mid-point between 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). During sap flow monitoring (11-18 June 2017) the 100-cm depth sensor in the PR2 probe malfunctioned. However, at that depth soil was continuously saturated or near saturated, and had shown no variation in soil water content the previous week, during which time daily measurements were made on all pits. Thus, we used soil water content values at 100-cm depth from sampling performed the previous week. We collected daily measurements from each tree pit for the duration of sap flow data collection, and on 10 and 17 June 2016 for water balance comparison between years. No supplemental irrigation was applied during these two periods. Weather data were obtained every 15 minutes from on-site monitoring equipment (Model ET106, Campbell Scientific, Inc., Logan, Utah, USA), including air temperature (ºC), air relative humidity (%), average wind speed ($m\ s^{-1}$), solar radiation ($W\ m^{-2}$), and air pressure (hPa). We calculated vapor pressure deficit (VPD) based on saturated vapor pressure estimations with the Tetens formula, as described in Murray (1967). We calculated the daily average for each parameter in order to estimate daily potential evapotranspiration with the FAO 2012 ETo calculator (Land and Water Digital Media Series Nº 36, FAO, Rome, Italy), based on Allen et al. (1998). Precipitation (mm) was totaled for the duration of sap flow data collection (seven days).

2.6 Water balance

2.6.1 Water balance for 11-17 June 2017

We calculated a water balance (Figure 3.1) for each of the 24 tree pits (Water Balance - Pit) and for the entire 168 m^2 study plot (Water Balance - Plot) during 11 June 2017–17 June 2017 when sap flow was monitored continuously.

Water Balance – Pit

For each tree pit we considered a tree-soil system comprised by the soil volume obtained from the 1-m^2 tree pit surface and a depth of 100 cm, corresponding to soil water content measurements (see Section 2.5), and the tree and leaf area above the pit within the 1-m^2 area defined by the tree pit. The water balance was calculated as:

$$I = O + \Delta S, \tag{1}$$

where I is water inputs, O is water outputs, and ΔS is change in water storage.

Inputs in Equation 1 were calculated as:

$$I = P, \tag{2}$$

where P is precipitation, recorded from the on-site weather station and added up the total rainfall for all dates during sap flow monitoring.

Outputs in Equation 1 were calculated as:

$$O = E_{soil} + T + DD + N_{leaf} + N_{stem} + S_p, \tag{3}$$

where E_{soil} is evaporation from the soil surface ($E_{soil\text{-}A}$ for bare soil, or $E_{soil\text{-}B}$ for soil covered with pavement), T is tree transpiration, DD is deep drainage, N_{leaf} is interception by leaf surfaces, and S_p is storage in the pavement and base course (assumed to evaporate from pavement).

Total tree transpiration was determined based on sap flow measurements as described in Section 2.3. At harvest, all trees were observed to have roots extending beyond the 1-m^2 tree pit into the surrounding impermeable area. This area, including the tree pit itself, encompasses approximately 16 m^2. This is comparable to expected root extent based on mean stem diameter (Day et al., 2010a). Thus, to calculate water extraction in the tree pit itself due to transpiration we divided total transpiration by this 16-m^2 root area, which also allowed us to convert it from L to mm (L/m^2 = mm).

We defined deep drainage as water movement to below 0.7 m in the soil profile. During the period when sap flow was monitored, we assumed *DD* to be negligible because soil water content readings at 60 cm depth were less than saturation, although it is possible that preferential flow along roots or unsaturated flow may have allowed some deep drainage to occur. Evaporation from the soil surface not covered by pavement was calculated with the method described by Allen et al. (1998) for bare soil. Based on daily calculated ETo, interval between rainfall events, and precipitation amounts (we used low infiltration depths), we obtained a daily crop coefficient for bare soil (K_c) for each of the 7 days of sap flow monitoring. K_c values ranged between 0.35 and 1.15. We multiplied this daily K_c by the daily ETo to find a daily soil evaporation. We then calculated the cumulative soil evaporation for the entire week ($E_{soil\text{-}A}$) by summing the daily values of soil evaporation:

$$E_{soil\text{-}A} = \Sigma(K_{c_i} * ET_{o_i}), \qquad (4)$$

Soil evaporation through the pavement ($E_{soil\text{-}B}$) was estimated as a percent of the cumulative potential evapotranspiration (CET_o) for the 7-day period, based on findings by Yuan et al. (2009). In their study, the ratio of evaporation from a loamy soil covered with a 5-cm thick gravel layer and held at 30% volumetric water content was approximately 25% for 2.5-cm gravel size, and 15% for 0.5-cm gravel size. In our study, the most restrictive gravel layer for air movement (and thus water vapor diffusion) was the resin-bound pea gravel, with a gravel size of 0.95 cm. By interpolation we estimated the average cumulative evaporation for the entire sap flow period ($E_{soil\text{-}B}$) as 17.25 % of the cumulative potential evapotranspiration (CET_o).

To estimate total tree rainfall interception by leaf surfaces, we multiplied tree leaf area by 1.1 mm, the leaf surface storage for *Platanus ×acerifolia* (Xiao and McPherson, 2016). We then calculated total rainfall for the canopy projection area, and subtracted leaf interception to get net rainfall. Net rainfall was divided by canopy projection area to normalize it for a 1-m^2 area (the tree pit), and then subtracted from total rainfall to get N_{leaf} normalized for the tree canopy projection over the tree pit. We estimated rainfall interception by the pavement by calculating the difference in weight of a dry, saturated, and drained sample of each pavement layer (resin bound gravel, #57 base course, and geotextile). We considered interception by tree stem surfaces (N_{stem}) to be negligible as the trees were young with smooth bark, while evaporation from leaf surfaces (E_{leaf}) was assumed to be equal to interception by leaf surfaces (N_{leaf}), as we observed drip to be minimal or absent for the rainfall events during sap flow monitoring. Evaporation of the water stored in the pavement (E_{pave}) was assumed to be equal to water stored in the pavement (S_p). Runoff (R) from the tree pit or into the tree pit was assumed to be zero, as such lateral surface flow was prevented by the raised frames on the tree pit edge. The week prior to sap flow monitoring we measured soil water content daily in the four PR2 probe tubes installed in the impermeable plastic section. We observed readings to be unresponsive to a comparable rainfall amount (14.55 mm) to what was received the following week. Therefore, we assumed Lateral Flow (LF) within the soil to be zero.

Change in Storage (ΔS) in Equation 1 was calculated with:

$$\Delta S = St_2 - St_1, \quad (5)$$

where St_1 and St_2 are water stored in the system at the beginning and end of sap flow monitoring (7-day period). Because water stored in pavement and on leaf and tree surfaces was assumed to evaporate, change in storage was measured by calculating volumetric soil water content of each horizontal soil section as measured with the 5TM sensors or PR2 probes. For the tree pits sampled with Delta-T PR2 Profile Probe, depth increments were 0-15 cm, 15-25 cm, 25-35 cm, 35-45 cm, 45-70 cm, and 70-100 cm. For tree pits sampled with Decagon 5TM soil moisture sensors, depth increments were 0-20 cm, 20-45 cm, and 45-100 cm. Thus storage was calculated:

$$S = \Theta_{10} * z_{0-15} + \Theta_{20} * z_{15-25} + \Theta_{30} * z_{25-35} + \Theta_{40} * z_{35-45} + \Theta_{60} * z_{45-70} + \Theta_{100} * z_{70-100} \quad (6)$$

where Θ is volumetric soil water content and z is soil depth.

Water Balance – Plot

Because tree root spread exceeded the pit dimensions, we calculated a second water balance for the entire study plot to better assess the full impact of trees in an urban streetscape. Estimations followed the same process as for Water Balance – Pit, except that all sap flow and soil volume was included such that spaces between tree pits were also included in the water balance. Thus, transpiration was calculated as the sum of all sap flow from study trees. As mentioned earlier, one of the sap flow gauges malfunctioned and those values were discarded. Thus, we assigned to that tree the same sap flow value as for another tree in the same treatment and with similar size, to calculate transpiration from all 12 trees. Soil water storage beneath the plastic covering was estimated using soil water content measurements at each depth increment from the four PR2 soil moisture sampling locations under the plastic covering and combined with pit estimates for storage.

2.6.2 Water balance for 11-17 June 2016

Based on Day et al. (2010a), by 2017 tree roots in our plot had likely extended between 2 and 3 m from trunks. This suggests that some tree pits may have had roots from adjacent plots extracting water through transpiration. However, in 2016, trees were considerably smaller and root intrusion into neighboring plots unlikely. Thus we calculated additional Water Balance – Pit and Water Balance – Plot for the same dates in the previous year (11-17 June 2016). Although we did not measure sap flow during 2016, soil water content and weather conditions were monitored and found to be comparable to the same dates in June 2017 (Table 3.1). Thus we calculated all variables in the balance using the methods described above, except for N_{leaf} and sap flow.

Because N_{leaf} was very small in 2017, we assumed N_{leaf} for these trees a year earlier, when they were smaller, to be negligible. Sap flow for 2016 was estimated with linear regression developed with 2017 stem cross-sectional area and sap flow: Sap flow (g) = -23332.88 + 5147.14*StemArea (cm^2) ($R^2 = 0.494$, $p = 0.0158$). Sap flow for 2016 was then estimated using stem cross-sectional area of each tree in 2016.

2.7. Statistical analysis

We compared differences of sap flux density and total tree transpiration between Tree-Paved and Tree-Unpaved using SigmaPlot 12 (Systat Software, Inc., San José, CA, USA). We used Student's t-test for sap flux density treatment comparisons. Total tree transpiration was not normally distributed, and we performed treatment comparisons using Mann-Whitney Rank Sum Test.

For the water balance (see Section 2.6), we also compared differences among treatments for Transpiration (T), Change in Storage (ΔS), and the value of inputs minus outputs using SigmaPlot 12. When normality assumptions were not met, we used a non-parametric test instead. For T (2016 and 2017) we used the Mann-Whitney Rank Sum Test; for ΔS (2016) we used a one-way ANOVA and Holm-Sidak method for multiple comparisons ($\alpha = 0.05$); for ΔS (2017) a one-way ANOVA; for the Balance (2016) a one-way ANOVA and Holm-Sidak method for multiple comparisons ($\alpha = 0.05$); and for the Balance (2017) the Kruskal-Wallis on Ranks test and Dunn´s method for multiple comparisons.

A linear regression equation was used to determine leaf area (Section 2.4) and 2016 sap flow (Section 3.2) using JMP software.

3. Results

Calculated VPD and ETo for 10-18 June 2017 together with a subset of observed weather parameters are shown in Figure 3.2.

3.1 Sap flux

There was no apparent treatment effect on sap flux (g/hr/cm^2) between Tree-Unpaved and Tree-Paved in 2017 (Table 3.2, Figure 3.3). The relationship between sap flux (g/h/cm^2) by unit leaf area and vapor pressure deficit (VPD) was similar for both Tree-Unpaved and Tree-Paved (Figure 3.4). However, there were higher sap flux values at higher VPD for Tree-Paved than for Tree-Unpaved. Total tree transpiration was larger for Tree-Paved than for Tree-Unpaved, but this was just because trees in Tree-Paved were larger than in Tree-Unpaved. This tree size difference between Tree-Unpaved and Tree-Paved, was even greater in 2016, and the estimated total sap flow was significantly higher for Tree-Paved than Tree-Unpaved (Table 3.2). In 11-17 June 2017, tree transpiration accounted for 33% of the outputs in Tree-Unpaved, and 64% for Tree-Paved (Figure 3.5).

3.2 11-17 June 2017 Water Balance – Pit

There was no statistically significant difference for water loss among treatments. However, pits with trees experienced a greater soil water loss from the system than those without trees, (Table 3.3, Figures 3.6 and 3.7). Pavement altered how soil water was removed from the tree-tree pit system, with a greater proportion of soil water leaving paved pits via transpiration (Figure 3.5).

Regardless of tree pit cover, Δ*S* decreased in pits with trees, with Tree-Paved having an average Δ*S* of -4.84% (SE=0.65) compared to -4.01% (SE=0.26) for Tree-Unpaved (Figure 3.7). Tree transpiration was 10.60 mm (SE=2.64) for Tree-Unpaved and was 16.97 mm (SE=1.75) for Tree-Paved (Table 3.3). Storage decreased in plots without trees resulting in a -3.21% (SE=1.34) Δ*S* for NoTree-Unpaved and -2.66% (SE=0.56) for NoTree-Paved.

The greater Δ*S* for pits with trees was also observed in the soil water content by depth. Tree-Unpaved had lower soil water content at 60-cm depth than NoTree-Unpaved, and Tree-Paved had lower soil water content at 30-cm depth than NoTree-Paved (Figure 3.8).

3.3 11-17 June 2016 Water Balance – Pit

In 2016, pits with trees also experienced an overall loss of water from the system, as indicated by a negative Δ*S*, while those without trees experienced a slight gain (Table 3.3, Figures 3.6 and 3.7). Again, pavement reduced this effect, with Δ*S* in Tree-Unpaved pits decreasing by an average of -3.44% (SE=0.037%) versus decreasing only -1.57% (SE=0.70%) in Tree-Paved pits (Figures 3.6 and 3.7). This reduction in storage was in spite of the greater total transpiration of the larger Tree-Paved trees [13.70 L (SE=0.85 L) and 5.12 L (SE=0.83 L) respectively] (Table 3.3). In contrast, Δ*S* in pits with no trees (NoTree-Unpaved and NoTree-Paved) increased by 0.62% (SE=0.38%) and 0.06% (SE=0.39%) respectively (Table 3.3, Figures 3.6 and 3.7).

3.4 11-17 June 2016-2017 Water Balance – Pit Comparison

As tree roots colonized the entire plot, change in soil water storage became less distinct between the tree pits with and without trees (Figure 3.7). Also, the impermeable area was at this time explored by roots, which were visually observed at harvest, and evident in the decrease in the amount of water stored in the soil in this area of the plot. Not only did NoTree-Unpaved and NoTree-Paved not have as much of a change in storage (Δ*S*) as Tree-Unpaved and Tree-Paved, but they instead gained water between 10 and 17 June 2016. The same week the following year, NoTree-Unpaved and NoTree-Paved had a comparable Δ*S* to treed plots (Figures 3.6 and 3.7).

The difference between the directly measured Δ*S* and the balance (Table 3.3) is an indicator of the reliability of our water balance estimation. This difference was larger in June 2017 than in June 2016. In June 2016, both NoTree-Unpaved and the area under the impermeable plastic (Impermeable) had a small difference between Δ*S* and balance. Tree-Paved had a smaller difference than Tree-Unpaved and NoTree-Paved. In June 2017, the difference between the balance and Δ*S* increased in all treatments except for Tree-Unpaved, which instead became smaller than in the previous year. This disparity of the difference between the balance and Δ*S* for 2016 and 2017 suggests that root exploration of larger soil volumes (which would have occurred in 2017) may have resulted in some water not being accounted for in the balance estimation. However, it might also be partly a result of our 2016 transpiration estimation.

3.5 11-17 June 2017 Water Balance – Plot

While calculating a water balance for the entire study area did not allow treatment comparisons, it incorporated the full extent of tree root systems and thus more closely represented water balance of an actual streetscape. In addition, the comparison between water balances provides insight into the contributions of extensive root exploration beneath adjacent impervious surfaces. The plot balance for 11-17 June 2017 was 108% greater than Δ*S* (Table 3.4). Transpiration volume was 8.18 times greater than soil evaporation from the study plot in 2017.

3.6 11-17 June 2016 Water Balance – Plot

Tree transpiration and Δ*S* were both lower for the study plot in 2016 than for the same week in 2017 (Table 3.4), likely due to trees realizing considerable size gains between 2016 and 2017 (de la Mota Daniel et al., 2018). In 2016, since trees were smaller, soil evaporation was a larger portion of the outputs than in 2017, and transpiration volume was only 1.86 times greater than soil evaporation (Figure 3.9). Thus, Δ*S* was 21.48 times greater in 2017 compared to 2016.

4. Discussion

4.1 Water Balance - Effect of Trees

Our estimated water balance was largely corroborated by direct measurements of change in storage (ΔS) (Figure 3.6 and Table 3.3). However, there were some discrepancies, especially in regards to ΔS overestimation in pits without trees, which we attribute to widespread root exploration of soil both within and beyond plot boundaries. For example, the plot balance for 11-17 June 2017 was 108% greater than ΔS (Table 3.4) indicating that there possibly was significant transpiration that was not accounted for in ΔS. Additional sources of error include possible deep drainage that bypassed deep soil layers through preferential flow along roots, and assumptions used in estimations of evaporation from pavement and bare soil.

When present, trees dominated water extraction from the soil. Change in soil water storage (ΔS) was statistically different among treatments for 2016. The lack of storage differences in 2017 shows the effect of root colonization everywhere in the plot (Table 3.3). We directly measured sap flux over one week in 2017 and found tree transpiration accounted for between 33% (Tree-Unpaved) and 64% (Tree-Paved) of water outputs. At the tree pit scale, between 11-17 June 2017, transpiration was over 100% of water inputs. For the entire study plot, for that same week, over 300% of water inputs to the pits were extracted through transpiration, considering only the rainfall that infiltrated through the pits. If we consider all precipitation on the plot (including rainfall on the impermeable area), transpiration at the plot level would still have been 101% of total rainfall. In our experiment, tree pits were designed so that no runoff from adjacent impermeable areas would reach the pit. However, in many urban scenarios there can be considerable pavement runoff into tree pits. In fact, many tree pits are designed specifically for bioretention and facilitate runoff collection from surrounding areas. Therefore, tree transpiration during the growing season could be somewhere between 100% and 300% of precipitation at the plot level when some of the runoff from adjacent pavement enters the pits, especially under smaller rainfall events. It is possible that with larger storm events, some of the runoff into the pits could leave as deep drainage instead of as tree transpiration. In a study in Illinois, USA, transpiration of trees growing in a swale to treat stormwater from a parking lot accounted between 46% and 72% of precipitation and irrigation water inputs (Scharenbroch et al., 2016), but unaccounted water was 18% to 49% of water inputs. The larger magnitude of transpiration over water inputs in our study suggests that stormwater management analyses should aim to account for transpiration of trees planted in tree pits in a paved streetscape during leaf-on periods.

As trees in our experiment grew and roots colonized the entire plot, it became difficult to quantify the water balance on a tree pit basis, yet this process provided valuable insight into the influence of trees in the streetscape. For example, the impermeable area outside of the tree pits was already explored by roots in June 2017. This root exploration throughout the plot is probably responsible for the difference between the measured ΔS and the calculated balance at the tree pit scale for NoTree-Paved and NoTree-Unpaved in 2017, compared to Tree-Unpaved and Tree-Paved (Table 3.3 and Figure 3.6). Specifically, this discrepancy was because the NoTree-Paved and NoTree-Unpaved pits, although lacking trees, were already influenced by root water extraction from neighboring trees. Once trees reached a certain size and colonized the nearby soil volume, root water extraction dominated the water balance, and homogenized soil water content at 10-cm depth, as well as change in storage (ΔS) during leaf-on periods, regardless of soil cover (impermeable pavement, permeable pavement or bare soil). A similar effect was observed by Volder et al. (2009) in Texas, USA with mature *Liquidambar styraciflua* L. where soil water content at 0-25-cm depth was not statistically different from soil under permeable concrete, impermeable concrete, and unpaved control.

This homogenization effect of tree roots on soil water content and storage is possibly also behind the observed similar values for sap flux between Tree-Unpaved and Tree-Paved, together with tree species related water relations. In a study in Utah, *Platanus ×acerifolia* (Aiton) Willd. showed poor stomatal control (Bush et al., 2008), which is consistent with its high reported stomatal conductance of 247 mmol m^{-2} s^{-1} (Leuzinger et al., 2010). In California that same species was unresponsive to shallow soil moisture in terms of daily sap flux (McCarthy and Pataki, 2010). In our study there was no treatment effect in tree sap flux between Tree-Unpaved and Tree-Paved, most likely because of poor stomatal control and because tree roots were already out of the tree pit area for both treatments. However, pavement did appear to affect the relationship between sap flux and VPD (Figure 3.4), with higher sap flux at higher VPD for Tree-Paved. This result may be a consequence of the roots in the drying surface soil in Tree-Unpaved signaling stomatal closure, leading to some response to fluctuating soil moisture levels at the soil surface. This pavement effect on sap flux likely varies depending on tree species, and suggests that further studies should investigate different combinations of tree species, pit design, and permeability of surrounding pavement to maximize soil water storage capacity from urban trees.

4.2 Water Balance – Soil Evaporation and Soil Cover

Another objective of our study was to quantify the influence of permeable pavement in the water balance. Permeable pavement may restrict evaporation from the soil surface even though it shifts soil moisture closer to the surface. The smaller ΔS of Tree-Paved in 2016 compared to Tree-Unpaved could be a result of the typically increased soil water content directly under pavement (Morgenroth and Buchan, 2009; de la Mota Daniel et al., 2018). The water balance for Tree-Unpaved from June 2017 left less water unaccounted for than that of 2016, even though transpiration withdrawal was likely overestimated in 2017 because trees were larger. Still, even in 2017 the proportion of transpiration attributed to pits was still 1/16. This discrepancy suggests an overestimation of evaporation from the soil in 2017. Evaporation from the soil surface may have been reduced because pit surfaces were largely shaded in 2017, but only partly shaded in 2016. In Tree-Unpaved direct evaporation from the soil reduced soil water storage, and compensated for the smaller tree size in Tree-Unpaved. In Tree-Paved, despite greater total transpiration, the condensation and distillation processes that occur under porous-permeable pavement (Morgenroth et al., 2013) possibly provided supplemental water to increase transpiration without an additional decrease in soil water storage. The faster growth rate of Tree-Paved trees (de la Mota Daniel et al., 2018) would be consistent with such an effect. This finding may be further supported by Tree-Paved trees being larger than Tree-Unpaved trees in 2016, probably with more roots already beyond the pit boundaries, affecting the partitioning of water extraction between within the pit and outside the pit areas. However, because trees in Tree-Paved grew faster and larger than in Tree-Unpaved, trees in Tree-Paved also eventually dried out the soil more, resulting in a greater ΔS in 2017, possibly because Tree-Paved pits had larger root systems than Tree-Unpaved, again, as a consequence of permeable pavement cover (de la Mota Daniel et al., 2018).

Furthermore although the majority of the roots were in the upper 60 cm of soil, we observed a few very deep roots that may have extracted water from deeper soil regions. The fact that the excess of transpiration at the whole study plot level in 11-17 June 2017 does not translate into an equivalent change in storage (ΔS) is probably further evidence of tree roots growing beyond the plot boundaries into adjacent areas and into the water table.

4.3 Implications for Urban Stormwater Management

Although our study looked at a small timeframe for the water balance (for example, compared to a yearly balance), it provides insight into the function of an element (the tree pit) of the urban system. Also, in many temperate areas of the world the leaf-on period for trees can be up to half of the year, and can be most or all of the year in subtropical and tropical regions. In our study, during a week in the growing season when trees were fully leafed out, transpiration became the main driver of the water balance at the plot level and resulted in an increase of soil water withdrawal by tree roots in June 2017 compared to June 2016. In regards to our study objective of considering implications of tree and permeable pavement presence, our findings show that regardless of soil cover, trees are a fundamental part of storm water mitigation practices because of their potential to increase the capacitance of the urban system through transpiration and, especially with mature trees, canopy rainfall interception. Furthermore, because tree roots can be widespread beneath pavement, trees may improve function of adjacent permeable pavements used for stormwater management. A recent study in Pennsylvania, USA investigated the sap flow response to rainfall events of several tree species (Gotsch et al., 2018). The species with no lag in sap flow response following a rain event were considered better suited as green infrastructure tools for stormwater management because they would increase sap flux faster after the storm event, as soon as energy from solar radiation was available. *Platanus occidentalis*, one of the parents of the tree in our study, *Platanus* ×*acerifolia*, did not show any lag in sap flow. We could expect *P.* ×*acerifolia* to behave similarly to *P. occidentalis*, thus increasing its value as an urban tree when used as a stormwater control measure.

Other studies have looked into quantifying urban tree transpiration and its contribution to the water balance (Asawa et al., 2017). However, these trees were planted in large containers used as lysimeters, and were neither field grown nor coupled with paved areas. This setup limits its applicability to actual urban tree growing conditions. However, urban trees often have restricted soil volume that restricts root exploration and tree development, and thus, transpiration and soil water extraction. Bartens et al. (2009) found that increasing the available soil volume through the use of structural soils can help maximize tree transpiration. In our study we found similar results in regards to the need to maximize tree growth in order to fully profit from tree transpiration for stormwater management. From June 2016 to June 2017, tree transpiration increased from 61% to 88% of the outputs at the plot level. Additionally, urban soils often limit tree growth due to reduced planting space (Sanders et al., 2013), stressing the need to develop tree pit-pavement-soil combinations that promote tree growth, increase tree transpiration, and thus, enhance watershed capacitance to further support the stormwater management role of centralized control measures. A combination of bare soil and permeable pavement of area equal to the tree canopy projection has been proposed to help increase water infiltration in the root-zone area, maximize cooling, and reduce tree water stress (Vico et al., 2014), although roots often extend well beyond tree canopy (Day et al. 2010). Better alignment of infiltration area with root spread would influence tree transpiration, soil water recharge and system capacitance. Based on our study, bare soil tree pits have a strong contribution to water outputs through direct soil evaporation, and porous-permeable pavements promote larger and faster tree growth. Therefore, increasing the size of bare soil tree pits and converting adjacent impermeable pavement to permeable pavement may yield the best results in order to improve stormwater management, compared with permeable-pavement covered tree pits and impermeable pavement surrounding, which is a common street installation in many cities. Also, permeable pavements with a thick coarse gravel subbase that allows for large water storage might increase capacitance, both through direct storage and potentially because of increased tree size, depending on the characteristics of the soil beneath the pavement (Mullaney et al., 2015a). In locations with a high water table and/or continuously wet soil, the cooling provided by tree transpiration may be a greater benefit than the change in storage (ΔS) in the system. In such cases, the system´s capacitance increase by trees might be less than that for systems with unsaturated soil profiles.

5. Conclusion

Trees play a significant role in the urban water balance of paved streetscapes. Even when trees are young, as in our study, they quickly became the dominant factor in the water balance during the growing season. Permeable pavements are sometimes considered as pervious surface for stormwater policy purposes, yet this work demonstrates that coupling trees with permeable pavements could contribute to stormwater management effectiveness by increasing watershed capacitance.

Soil-pavement combinations that facilitate root exploration and water withdrawal may be valuable in many climates and should be considered in future urban planning and redevelopment. Our experiment took place in a humid climate and with one tree species. Other climates may require further consideration of aligning tree species and local conditions. For example, in arid climates, water scarcity will need to be considered. Regardless, maximizing tree size is fundamental to increase the ability of trees to transpire water and increase stormwater retention capacity, as well as other ecosystem services provided by urban forests.

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Figures and Tables

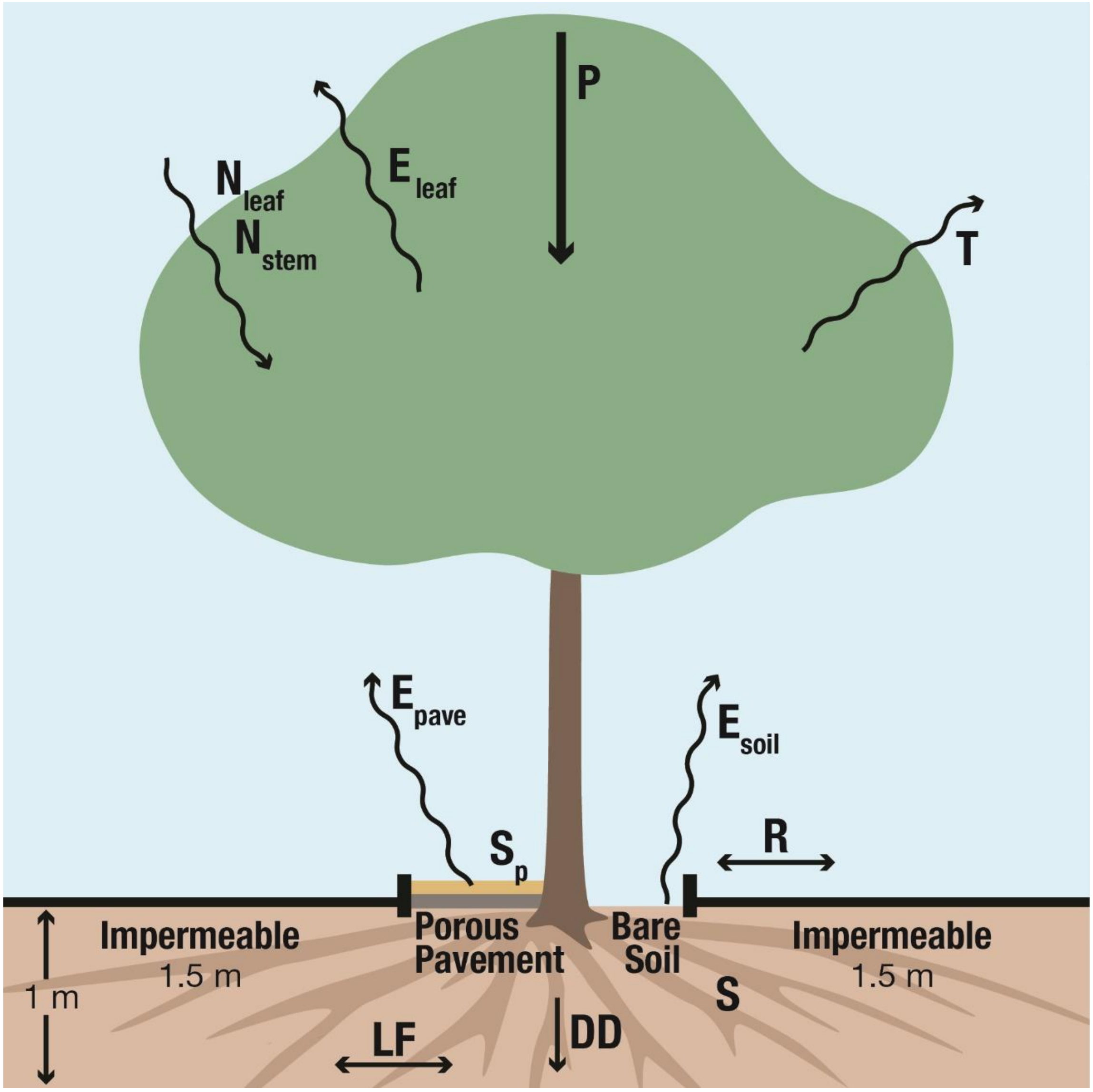

Figure 3.1. Conceptual diagram of water balance for a tree pit installed in an impervious area, showing both bare soil tree pit and permeable pavement cover (not to scale). Image by Sarah Gugercin.

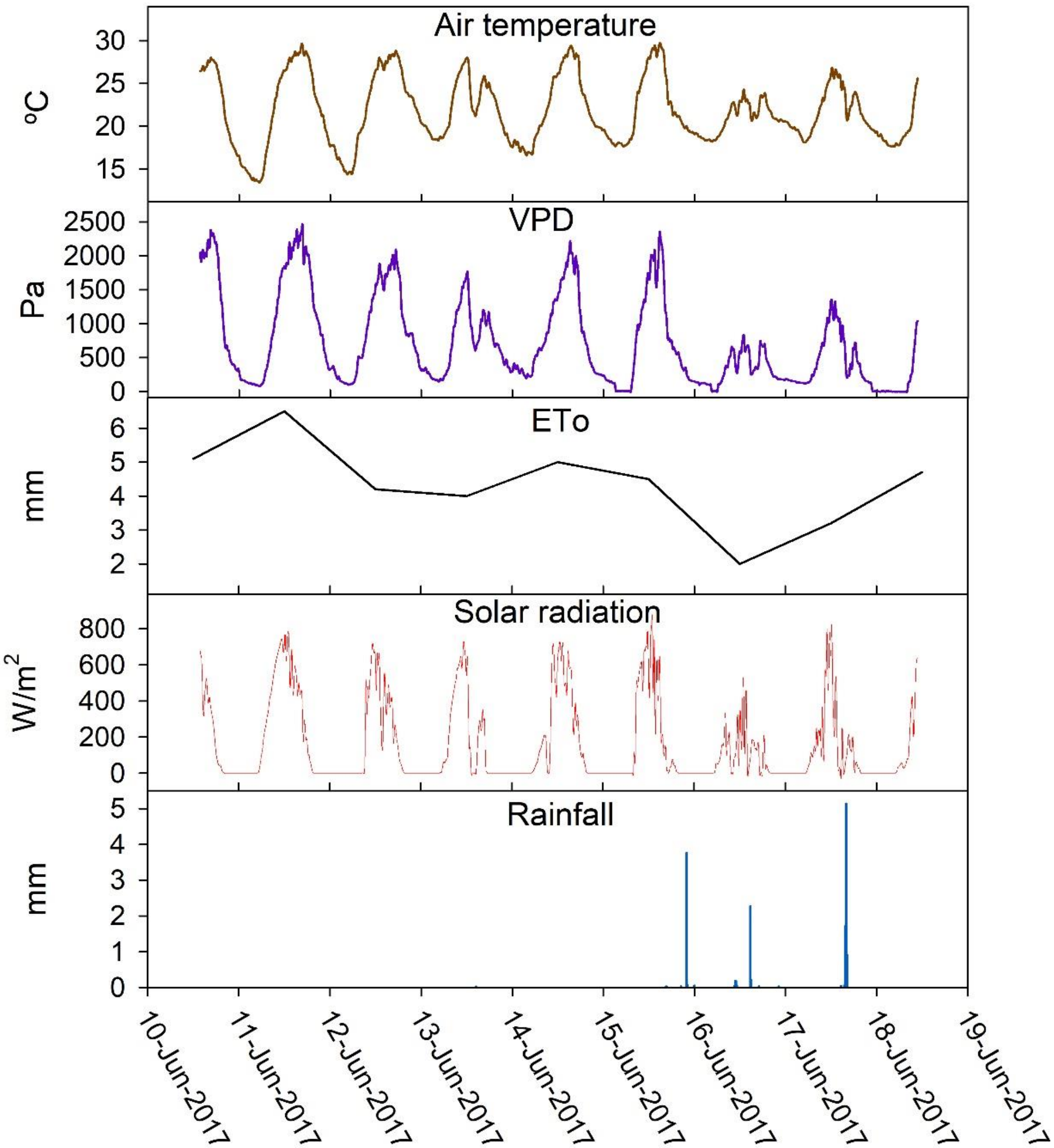

Figure 3.2. Air temperature, vapor pressure deficit (VPD) and solar radiation (15-minute mean), daily potential evapotranspiration (ETo), and 15-minute cumulative rainfall for 10-18 June 2017 at the experimental site in Blacksburg, VA, USA.

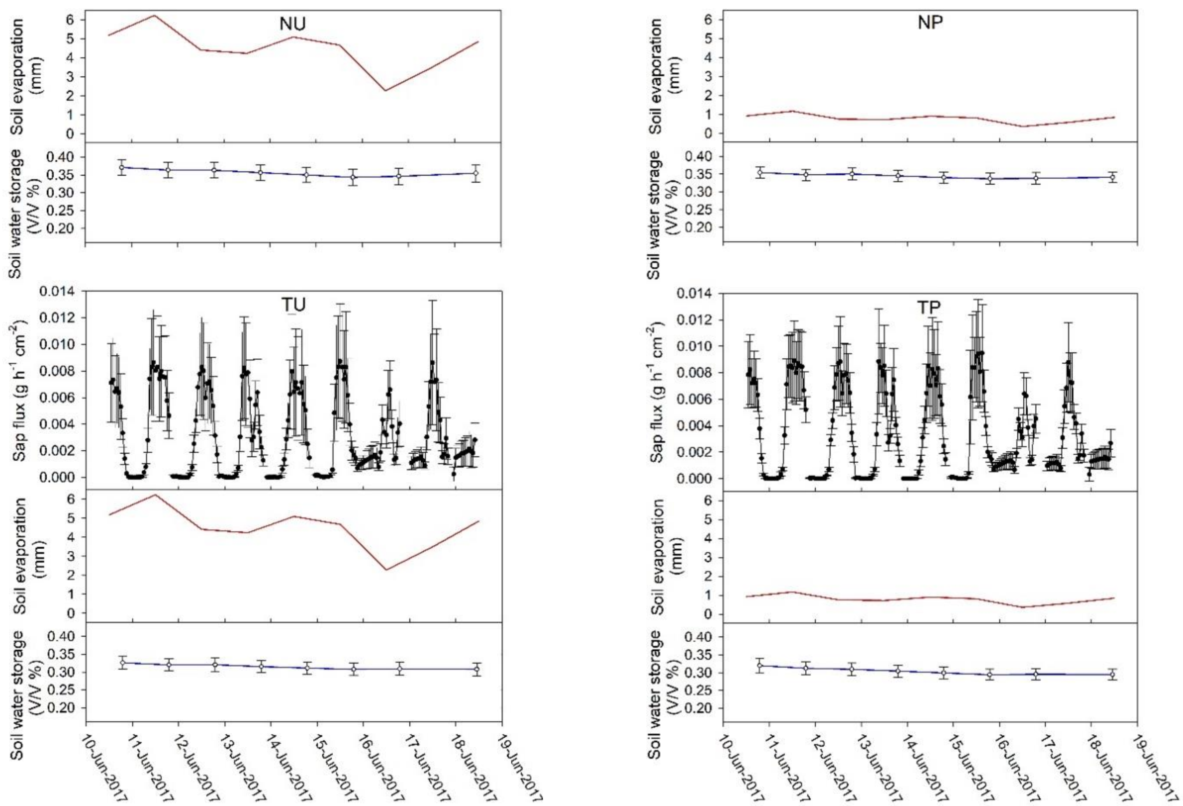

Figure 3.3. Sap flux per unit leaf area, soil water evaporation, and soil water storage for 10-18 June 2017, for tree pits ($1m^3$) with bare soil (NoTree-Unpaved, NU), tree pits with porous pavement (NoTree-Paved, NP), and tree pits planted with *Platanus ×acerifolia* ‘Bloodgood’, with and without porous pavement cover (Tree-Paved, TP, and Tree-Unpaved, TU, respectively). Error bars represent the standard errors of the means (n=6, except for Tree-Unpaved where n=5, and for soil evaporation where n=1).

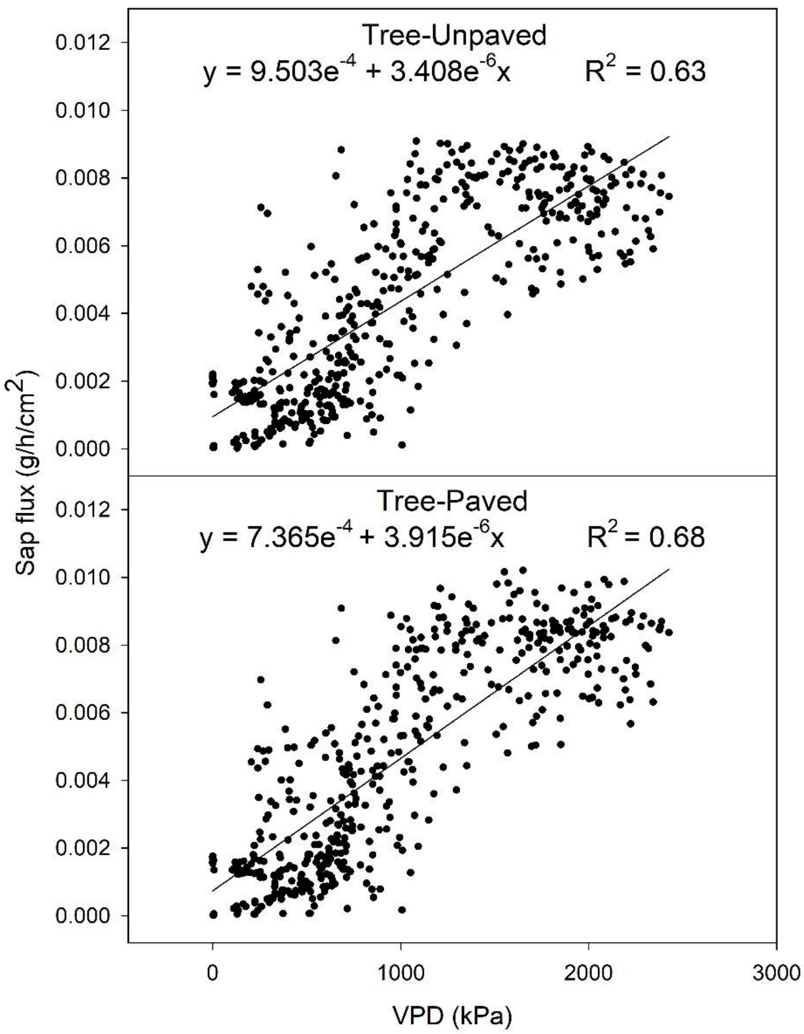

Figure 3.4. Relationship between sap flux per unit leaf area and atmospheric vapor pressure deficit (VPD) for 10-18 June 2017, for *Platanus ×acerifolia* ‘Bloodgood’ trees planted in tree pits with porous pavement cover (Tree-Paved, n=6) and without porous pavement cover (Tree-Unpaved, n=5).

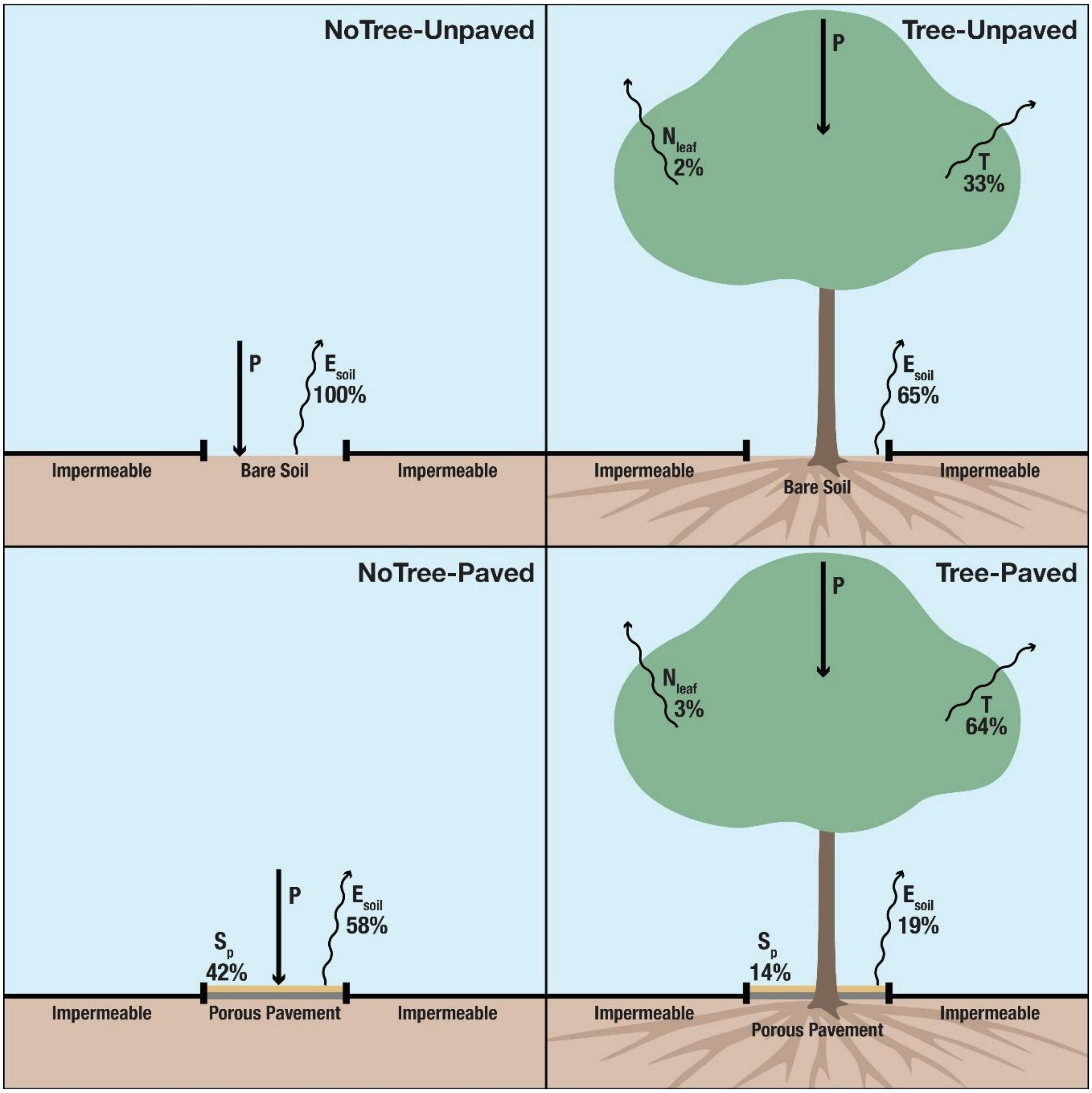

Figure 3.5. Conceptual diagram (not to scale) of water balance for tree pits with bare soil (NoTree-Unpaved), tree pits with porous pavement (NoTree-Paved), and tree pits planted with *Platanus ×acerifolia* 'Bloodgood', with and without porous pavement cover (Tree-Paved and Tree-Unpaved, respectively). Values shown are the percent of the total water outputs for each treatment for 11-17 June 2017. Image by Sarah Gugercin.

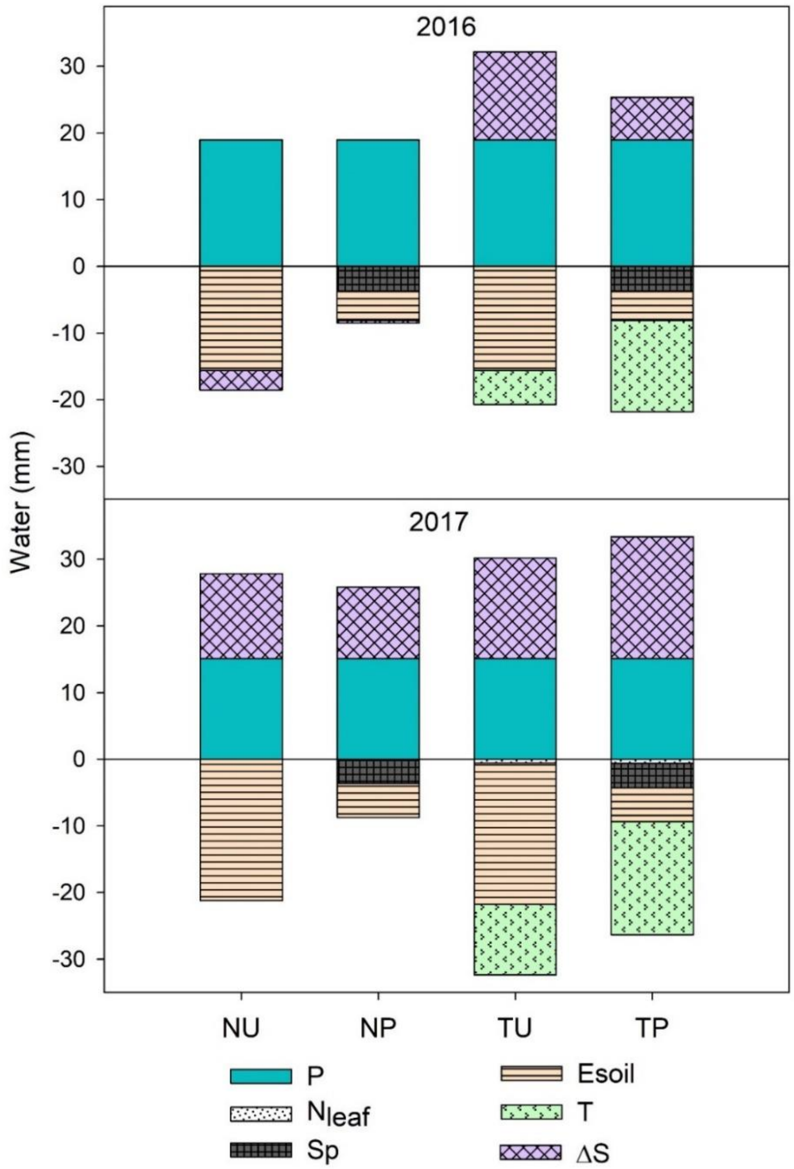

Figure 3.6. Water balance components calculated by treatment for 11-17 June 2016 and 11-17 June 2017, for tree pits ($1m^3$) with bare soil (NoTree-Unpaved, NU), tree pits with porous pavement (NoTree-Paved, NP), and tree pits planted with *Platanus ×acerifolia* 'Bloodgood', with and without porous pavement cover (Tree-Paved, TP, and Tree-Unpaved, TU, respectively). Input is rainfall (*P*) and appears above the 0 line. Outputs appear below the 0 line and include tree leaf rainfall interception (N_{leaf}), porous pavement storage (S_p), evaporation (E_{soil}) from bare soil (NU and TU) and from soil covered with porous pavement (NP and TP), and tree transpiration (*T*). When change in storage (ΔS) is negative, it appears with the inputs. When ΔS is positive, it appears with the outputs. Number of replicates n=6, except for TU where n=5.

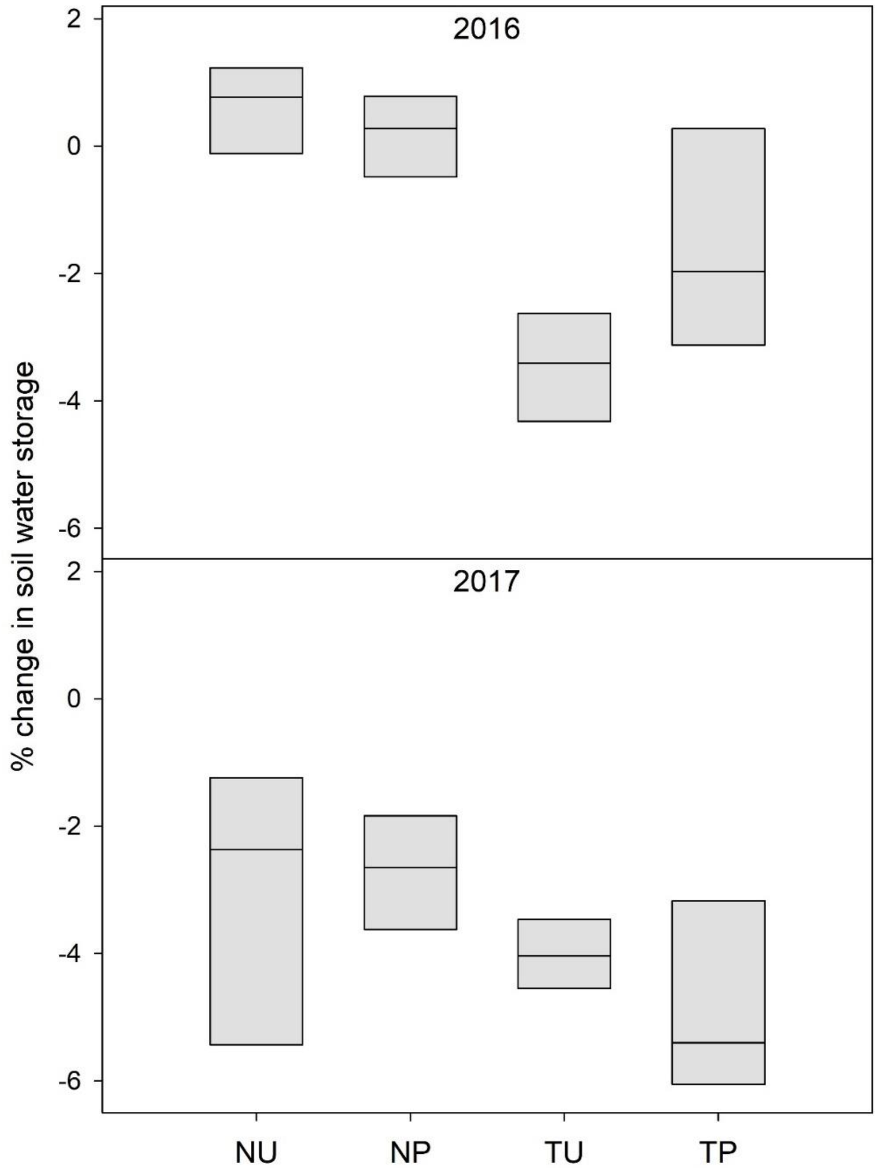

Figure 3.7. Percent change in soil water storage by treatment (n=6) for 11-17 June 2016 and 11-17 June 2017, for tree pits (1m3) with bare soil (NoTree-Unpaved, NU), tree pits with porous pavement (NoTree-Paved, NP), and tree pits planted with Platanus ×acerifolia 'Bloodgood', with and without porous pavement cover (Tree-Paved, TP, and Tree-Unpaved, TU, respectively). Bars represent mean and interquartile range.

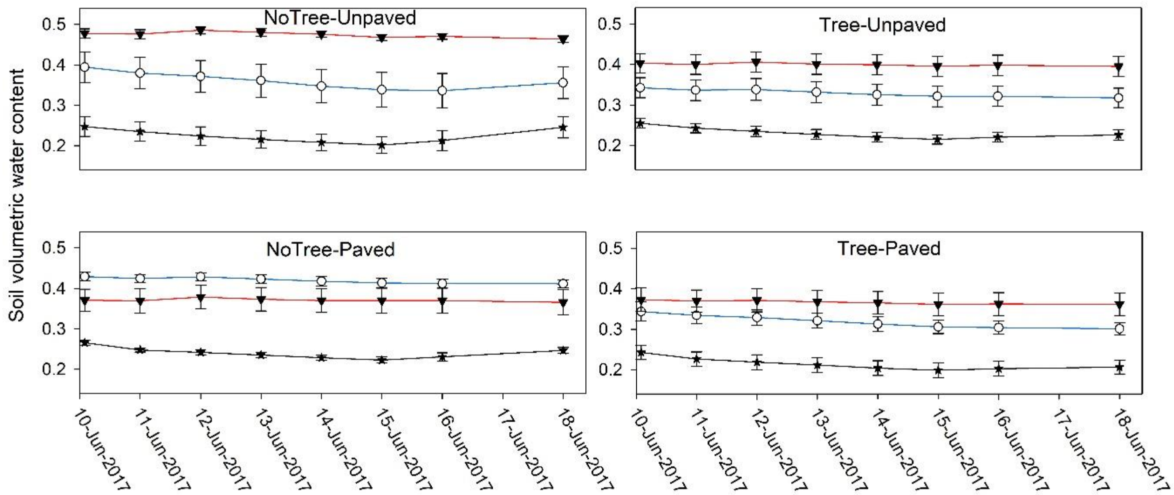

Figure 3.8. Change in soil volumetric water content at 10-, 30-, and 60-cm depths below soil surface for tree pits for 10-18 June 2017, for tree pits with bare soil (NoTree-Unpaved), tree pits with porous pavement (NoTree-Paved), and tree pits planted with Platanus ×acerifolia 'Bloodgood', with and without porous pavement cover (Tree-Paved and Tree-Unpaved, respectively). Error bars represent standard errors of the means (n=6).

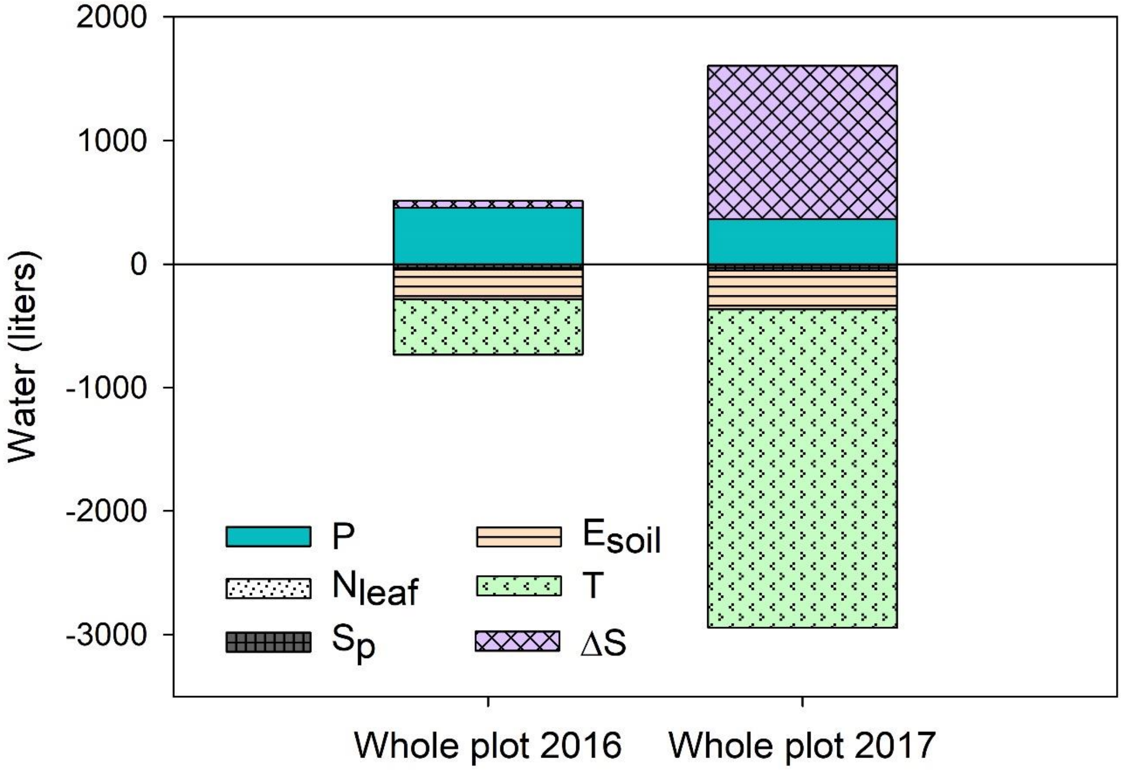

Figure 3.9. Water balance including change in storage (Δ*S*) for the whole study plot (168 m^3) for 11-17 June 2016 and 11-17 June 2017. Study site surface was impermeable except for 6 tree pits with bare soil (NoTree-Unpaved), 6 tree pits with porous pavement (NoTree-Paved), and 12 tree pits planted with *Platanus* ×*acerifolia* 'Bloodgood', with (6) and without (6) porous pavement cover (Tree-Paved and Tree-Unpaved, respectively). Input is rainfall (*P*) and appears above the 0 line. Outputs appear below the 0 line and include tree leaf rainfall interception (N_{leaf}), porous pavement storage (S_p), evaporation (E_{soil}) from bare soil (NoTree-Unpaved and Tree-Unpaved) and from soil covered with porous pavement (NoTree-Paved and Tree-Paved), and tree transpiration (*T*) (n=6).

Table 3.1. Weather parameters (from onsite weather station) and soil water storage comparison between 11-17 June 2016 and 11-17 June 2017. Air temperature, relative humidity (RH), wind speed, daytime solar radiation, and vapor pressure deficit (VPD) calculated as the weekly mean. Rainfall calculated as weekly total accumulation. Soil water storage calculated as the tree pit mean at the beginning of sap flow monitoring (10 June 2016, n=24, SE= 7.85; 10 June 2017, n=23, SE= 7.76).

	11-17 June 2016	**11-17 June 2017**
Air temperature (ºC)	22.02	21.80
RH (%)	63.72	76.80
Wind speed (m/s)	1.48	0.93
Solar radiation (W/m^2)	284.9	253.3
Rainfall (mm)	18.99	15.14
VPD (Pa)	1088.95	712.50
Soil water storage (mm)	427.66	390.14

Table 3.2. Sap flux density and total tree transpiration for tree pits planted with Platanus ×acerifolia 'Bloodgood', with and without porous pavement cover (Tree-Paved and Tree-Unpaved, respectively) for 11-17 June 2017.

	Tree-Unpaved		**Tree-Paved**		
	Average	**(SE)**	**Average**	**(SE)**	***p***
Sap flux (g/h/cm-2) - leaf area	0.0032	0.0006	0.0034	0.0004	0.79 †
Sap flux (g/h/cm-2) - stem area	28.33	3.54	30.69	2.96	0.36 †
Total tree transpiration (L)	169.52	42.20	271.52	27.98	0.08 ‡
Total tree transpiration (L) 1m^2	10.60	2.64	16.97	1.75	0.08 ‡

† Student's T-test. ‡ Mann-Whitney Rank Sum Test.

Table 3.3. Effect of porous pavement and tree transpiration on the water balance components by treatment for 11-17 June 2016, and 11-17 June 2017 for tree pits (1m^3) with bare soil (NoTree-Unpaved), tree pits with porous pavement (NoTree-Paved), tree pits planted with *Platanus ×acerifolia* 'Bloodgood', with and without porous pavement cover (Tree-Paved and Tree-Unpaved, respectively), and four soil water content sampling locations under the impermeable soil cover. Input is rainfall (P). Outputs are tree leaf interception (N_{leaf}), porous pavement storage (S_p), evaporation (E_{soil}) from bare soil (NoTree-Unpaved and Tree-Unpaved) and from soil covered with porous pavement (NoTree-Paved and Tree-Paved), and tree transpiration (T). The difference between the observed change in storage (ΔS) and the calculated balance is also shown (n=6, except for Tree-Unpaved where n=5, and Impermeable n=4). Different letters indicate statistical significance at α = 0.05 level.

2016	NoTree-Unpaved		NoTree-Paved		Tree-Unpaved		Tree-Paved		Impermeable		
	Average	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**p-value**
***P* (mm)**	18.99	-	18.99	-	18.99	-	18.99	-	-	-	
N_{leaf} (mm)	-	-	-	-	0.00	0.00	0.00	0.00	-	-	
S_p (mm)	-	-	3.67	-	-	-	3.67	-	-	-	
E_{soil} (mm)	15.60	-	4.45	-	15.60	-	4.45	-	-	-	
***T* (mm for 7 days)**	-	-	-	-	5.12[a]	0.83	13.70 [b]	0.85	-	-	0.0081 †
$\Delta S = S_{t2} - S_{t1}$ (mm)	2.96[a]	1.63	0.35 [ac]	1.54	-13.19 [b]	1.69	-6.36 [bc]	2.98	0.49	0.01	0.0002 ‡
Balance	3.39 [a]	-	10.87 [b]	-	-1.73 [c]	0.83	-2.83 [c]	0.85	0.00	-	< 0.001 ‡
Difference	0.43	1.63	10.52	1.54	11.46	2.05	3.53	3.14	-0.49	0.01	

† Mann-Whitney Rank Sum Test. ‡ One-way ANOVA. All Pairwise Multiple Comparison Procedures (Holm-Sidak method).

2017	NoTree-Unpaved		NoTree-Paved		Tree-Unpaved		Tree-Paved		Impermeable		
	Average	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**Average**	**(SE)**	**p-value**
***P* (mm)**	15.14	-	15.14	-	15.14	-	15.14	-	-	-	
N_{leaf} (mm)	-	-	-	-	0.57	0.05	0.63	0.03	-	-	
S_p (mm)	-	-	3.67	-	-	-	3.67	-	-	-	
E_{soil} (mm)	21.20	-	5.07	-	21.20	-	5.07	-	-	-	
***T* (mm for 7 days)**	-	-	-	-	10.60[a]	2.64	16.97 [a]	1.75	-	-	0.08 †
$\Delta S = S_{t2} - S_{t1}$ (mm)	-12.72 [a]	5.29	-10.72 [a]	2.36	-15.05 [a]	1.05	-18.26 [a]	2.66	-6.36	1.49	0.43 ‡
Balance	-6.06 [c]	-	6.40 [ac]	-	-17.22 [bc]	2.66	-11.20 [bc]	1.76	0.00	-	< 0.001 §
Difference	6.66	5.29	17.12	2.36	-2.17	2.07	7.05	3.06	6.36	1.49	

† Mann-Whitney Rank Sum Test. ‡ One-way ANOVA. § Kruskal-Wallis One Way Analysis of Variance on Ranks. All Pairwise Multiple Comparison Procedures (Dunn's Method).

Table 3.4. Values for the different components of the water balance equation calculated at a plot level (168 m3) for 11-17 June 2016 and 11-17 June 2017: rainfall (*P*), tree leaf rainfall interception (N_{leaf}), porous pavement storage (S_p), evaporation (E_{soil}) from bare soil (NoTree-Unpaved and Tree-Unpaved) and from soil covered with porous pavement (NoTree-Paved and Tree-Paved), 12 Platanus ×acerifolia 'Bloodgood' trees transpiration (*T*), change in storage (Δ*S*), and the difference between Δ*S* and the calculated balance.

Whole Plot	2016	2017
P (L)	455.76	363.36
N_{leaf} **(L)**	0.00	7.01
S_p **(L)**	44.03	44.03
E_{soil1} **(L)**	187.17	254.40
E_{soil2} **(L)**	53.41	60.86
T (L for 7 days)	448.00	2577.27
$\Delta S = S_{t2} - S_{t1}$ **(L)**	-57.83	-1242.02
Balance	-276.85	-2580.21
Difference	-219.02	-1338.19

Chapter 4

HYDRUS-1D Modeling of Water Movement in Permeable Pavement and Soil Layers in Tree Pit Systems

Abstract

Trees growing in dense urban areas provide many ecosystem services. However, these benefits may be diminished when tree growth is restricted by restricted soil volumes in the pavement cutouts where trees are planted (tree pits). Tree pits traditionally have been left unpaved, but in recent years, permeable pavements are being used to cover the soil surface. However, pavements may alter soil water content and root depth distribution. By understanding soil water content patterns in constructed and layered urban soils, tree pits can be designed to improve tree health, minimize root-pavement conflicts, and capture stormwater.

In order to predict soil water content in these pavement-tree urban systems, we calibrated and validated HYDRUS-1D for summer 2016, and ran simulations for different pavement thicknesses and root distributions. For this purpose, we installed 24 simulated tree pits either covered with porous-permeable resin-bound gravel pavement, or left unpaved, at two different sites in Virginia, USA. Each pit was then either planted with *Platanus ×acerifolia* 'Bloodgood' trees, or left without trees. We characterized the soil profile and monitored root development as well as soil water content at several depths.

The best fit between observed soil water contents and values predicted by HYDRUS-1D was achieved closer to the soil surface, being better at 10 and 30 cm than at 60 cm. The model achieved a maximum Nash-Sutcliffe efficiency for 10 cm soil water content in the planted and paved tree pits (NSE = 0.45). Increases in pavement thickness did not change simulated soil water content at any depth at the Mountains site, but it increased at 10- and 30-cm depths, and decreased at 60-cm depth, at the Coastal Plain site. This difference was due to soil textural differences rather than climatic conditions. Because water content in the upper 30 cm of soil provides a strong control on tree root soil exploration and pavement interactions, HYDRUS-1D has strong potential as a tool to predict relevant soil water

content patterns and likely root distribution in response to typical urban tree planting site designs, including those covered with permeable pavement.

Keywords: soil water, pervious pavement, tree roots, water infiltration, streetscapes

1. Introduction

Trees growing in dense urban areas confront a challenging environment that often includes restricted soil volumes and compacted soils, resulting in reduced growth (Grabosky and Gilman, 2004) and health (Patterson, 1977; Hawver and Bassuk, 2007). Healthy trees provide many ecosystem services including stormwater runoff control, urban heat island mitigation, and beautification, among others (Livesley et al., 2016). Thus, providing adequate soil volume is relevant to ecosystem service provision by trees. However, in dense urban areas the only soil volume available for full root exploration may be the cutouts in the pavement (tree pits) where trees are planted. The majority of the remainder of the soil is often compacted and its surface covered with impermeable pavement for pedestrian or vehicle use.

Soil moisture distribution affects root growth opportunity (Day et al., 2000), and thus predicting how moisture will be distributed in tree pit environments is of great interest. Pavement itself modifies soil moisture distribution (Morgenroth and Buchan, 2009; Volder et al., 2009; Mullaney et al., 2015a; Fini et al., 2017; de la Mota Daniel et al., 2018) and impervious pavement limits water infiltration into the soil. Soil water content is typically greater directly under pavement (Morgenroth and Buchan, 2009; de la Mota Daniel et al., 2018). Among other concerns, this increased soil moisture directly under pavement and the soil compaction necessary to bear pavement and vehicle loads results in the interface between the soil surface and the pavement being the preferential area for root growth.

Tree pit design varies by region, but the soil surface within the pavement cut out has traditionally have been left unpaved, or covered with iron grates level with the adjacent sidewalk. Permeable pavements are now also being used in place of grates to cover tree pits and provide a continuous level walking surface. However, permeable pavements are known to modify soil water content as well as root depth distribution, for example promoting shallow root development (Morgenroth and Buchan, 2009; de la Mota Daniel et al., 2018). Subsequent root-pavement conflicts can result in sidewalk damage, which increase maintenance costs in cities and towns (Randrup et al., 2001). Engineers and urban foresters have looked into ways to solve this problem. Structural soils (Grabosky and Bassuk, 1995) and suspended pavements (Page et al., 2015) are being used as means to mitigate soil compaction, manage stormwater, and promote tree growth. It is of interest to understand water flow in these constructed systems, however, measuring soil water content in actual urban installations is costly and complex. Furthermore, knowing soil water content may not necessarily provide us information on water fluxes in these systems. Therefore, a better understanding of soil water content patterns in constructed and layered soil systems would be beneficial to inform tree pit and street design with the goal of improving tree health, minimizing root-pavement conflicts, and capturing storm water.

Modeling may be a useful tool to predict soil water content in these pavement-tree urban systems. Furthermore, since roots grow preferentially in areas with greater water content, we could have the information to estimate the preferential root growth zones in soil profiles under permeable pavement based on soil water content distribution. Many computer tools have been developed to solve problems related to water flow in soil environments. These computer models are generally used to understand processes that cannot be solved analytically due to their complexity, and that need to be solved numerically. These computer models are today fundamental tools for studying vadose zone flow and transport processes (Šimůnek et al., 2008) and are increasingly being used in natural subsurface systems (Šimůnek and de Vos, 1999). Permeable pavements have fewer modeling tools available to understand their hydraulic characteristics compared to other low impact development (LID) practices, and their numerical modelling is complex (Brunetti et al., 2016). For example, the EPA Storm water Management Model (SWMM) can be used for water flow modelling in LIDs (Gironás et al., 2010), but its accuracy in these situations can be low (Zhang and Guo, 2015).

Another modeling tools is HYDRUS (Šimůnek et al., 1998). HYDRUS is a modeling environment that analyzes both saturated and unsaturated water flow through layered porous media, and in combination with *in situ* measurements provides a powerful tool for estimating water fluxes below ground in a variety of scenarios (Newcomer et al., 2014). HYDRUS includes not only parameters describing fluxes through layered soils, but also soil response to water withdrawal by roots (Wu et al., 1999). These data can then be used to estimate soil water status at every depth in the profile under different soil profile scenarios, allowing results to be used in many settings and situations. A few studies have tested HYDRUS to describe the hydraulic behavior of pavements (Illgen et al., 2007; Carbone et al., 2014). The Carbone et al. (2014) study used HYDRUS-1D on the premise of potentially better describing preferential flows due to the unsaturated behavior of pavement. Illgen et al. (2007) calibrated HYDRUS-2D with observational data on different types of permeable pavement, and then simulated a set of different conditions. HYDRUS-2D has also been used to predict soil water recharge in bioinfiltration sites (Newcomer et al., 2014). However, it has never been utilized in conventional urban tree planting sites. It should be possible to predict soil water content distribution under pavements and thus, estimate preferential root growth for designing better pavement sections to reduce tree-infrastructure conflicts, and to manage stormwater.

The objective of this study was to use empirical data to calibrate and validate HYDRUS-1D with hourly data for the summer of 2016, and to assess its suitability as a tool to understand soil water behavior under permeable pavements in urban tree pits. Additionally, we will use simulations of soil water content in constructed soil profiles under different permeable pavement thicknesses and root depth distributions to investigate the potential of HYDRUS-1D as a tool to inform engineers on pavement design and tree integration in urban landscapes.

2. Materials and Methods

2.1 Experimental sites

This experiment took place at two sites in Virginia, USA, with different climates and soils: the Urban Horticulture Center in Blacksburg, VA, USA (Lat. 37.218739, Long. 80.463679, Elev. 622 m) in the Valley and Ridge physiographic region (Mountains); and the Hampton Roads Agricultural Research and Extension Center in Virginia Beach, VA, USA (Lat. 36.893721, Long. 76.177655, Elev. 9 m.) in the Coastal Plain physiographic region (Coastal Plain). The Mountains site has a humid continental climate (Dfb classification by

Köppen) while the Coastal Plain site has a humid subtropical climate (Cfa classification by Köppen). In the Mountains, annual mean temperature is 10.9 °C, and annual mean precipitation is 1038 mm, while in the Coastal Plain they are 15.3 °C, and 1200 mm, respectively.

2.2 Experimental design and installation

Each experimental site had 24 simulated tree pits (Figure 4.1), either planted with *Platanus ×acerifolia* 'Bloodgood' trees, or without tree, as well as covered with porous-permeable resin-bound gravel pavement, or unpaved. These treatment combinations were applied in a completely randomized design as: 1) paved tree pit and no tree (NoTree-Paved), 2) unpaved (bare soil) tree pit and no tree (NoTree-Unpaved), 3) paved tree pit and tree (Tree-Paved), and 4) unpaved tree pit and tree (Tree-Unpaved). We constructed the tree pits with 1 m × 1 m treated wooden frames, with a 1.5-m spacing. We killed existing herbaceous vegetation with glyphosate and eliminated it manually to minimize soil disturbance. In the unpaved treatments, we also suppressed weed growth over the course of the experiment with glyphosate.

In many cities, the paved areas between tree pits are impermeable. To reproduce this setup, we covered the entire plot area at both sites with 0.254-mm black polyethylene sheeting and we cut it out over the pits. To prevent surface water runoff into the pits we stapled the sheeting to the top of the wooden frames. We then covered the plastic with a 10-cm layer of woodchips to hold it in place and prevent soil from heating excessively. At each site we planted 12 *Platanus ×acerifolia* 'Bloodgood' two-year-old bare-root whips grown from rooted cuttings (Carlton Plants LLC Dayton, OR, USA). Trees were approximately 1.2 cm in diameter at 15 cm above ground, and we pruned them to 110 cm height. We also pruned the root systems to 20 cm x 20 cm x 20 cm to standardize and minimize soil disturbance at planting. The original planting dates were 11 November, 2014 (Mountains) and 16 December, 2014 (Coastal Plain). However, at the Coastal Plain site one tree in the Tree-Paved treatment and one in the Tree-Unpaved treatment did not survive. We replaced them with reserved planting stock on 9 July 2015.

After planting we covered 12 tree pits (6 in Tree-Paved and 6 in NoTree-Paved) with porous-permeable resin-bound gravel pavement, which included: 1) a sheet of non-woven geotextile (DuPont™ Typar® SF27 90 g·m^{-2}, DuPont™ Typar® Geosynthetics, Luxembourg) laid over the soil surface; 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-liter batches with 500 ml of Gravel-Lok™ (Cell Tek LLC., Crofton, MD, USA), a polyurethane binder (Figure 4.2).

2.3 Soil characterization

The Mountains site has a Groseclose-Poplimento soil series complex (fine, mixed, subactive, mesic Ultic Hapludalf) and the Coastal Plain site has a Tetotum loam (fine-loamy, mixed, semiactive, thermic Aquic Hapludults).

At both sites, we took two types of soil samples: with a trowel for particle size analysis, and soil cores with a bulk density hammer for saturated hydraulic conductivity and water holding capacity. At the Mountains site on 27 and 28 June 2014 we took eight samples of each method at 10- and 60-cm depths (horizons A and B, respectively). At the Coastal Plain site on 3 July 2014, we collected five samples of each method at 10-, 40- and 80-cm depths (horizons A, B_t and C). The sampling locations were evenly distributed throughout the entire plot area in the space between the tree pits, not in the pits.

We used a pressure plate to determine soil water holding capacity (Richards, 1941) and determined soil water content at -0.033, -0.3 and -1.5 MPa. We then used these data to create soil water retention curves for each soil horizon, and estimate the Van Genuchten parameters α and n based on Anlauf (2014). We estimated saturated hydraulic conductivity with the falling head method using a Ksat instrument (UMS GmbH, Germany). We used a $CaCl_2$ 0.10 M solution to avoid clay deflocculation, and ran the test three times for each soil core, calculating the average value. Soil properties are presented in Table 4.1.

The saturated hydraulic conductivity of gravel is considered to be between 10^{-3}- and 1 cm·s^{-1} (Chapuis, 2004), depending on particle size. In our experiment we used 9.5 mm pea gravel bound with a polymer which, inevitably, reduces the pore space within the gravel. Also the geotextile used loses permeability over time due to clogging. Therefore, we assumed the saturated hydraulic conductivity of the pavement in our experiment to be on the lower end of this range, or 10^{-2} cm·s^{-1}.

2.4 Soil water monitoring

Between May and August of 2016, we continuously monitored volumetric soil water content at 10-, 30- and 60-cm depths at one replicate per treatment with Decagon 5TM capacitance soil sensors (Decagon Devices, Inc., Pullman, WA, USA). Data was collected every 15 minutes, except when raining, when it was collected every 5 minutes, when prompted by a Decagon LWS leaf wetness sensor (Decagon Devices, Inc., Pullman, WA, USA). In the other 20 tree pits, we measured volumetric soil water content weekly (Mountains site) or monthly (Coastal Plain site) at 10-, 20-, 30-, 60- and 100-cm depths with a PR2/6 capacitance probe and DL6 datalogger (Delta-T Devices Ltd., Cambridge, United Kingdom), and calculated the average.

2.5 Weather data

We obtained weather parameters from on-site monitoring equipment (Model ET106, Campbell Scientific, Inc., Logan, Utah, USA), including air temperature (ºC), air relative humidity (%), average wind speed (m s^{-1}), solar radiation (W m^{-2}), and precipitation (mm). Data was collected every 15 minutes and we calculated the hourly average (air temperature, air relative humidity, wind speed) or hourly total (precipitation). At the Mountains site there was some missing weather data scattered throughout the three-month period (several hours for 16 days) that was interpolated, except for rainfall where we used the NASA NLDAS-2 dataset for Blacksburg, VA (Goddard Earth Sciences Data and Information Services Center, NASA Goddard Space Flight Center, Code 610.2, Greenbelt, MD 20771 USA, http://disc.gsfc.nasa.gov).

2.6 Tree physiological data

We monitored root distribution by depth in the soil profile with minirhizotron tubes. For a detailed description of the method see Chapter 1.

We also estimated leaf area index for the summer of 2016, based on actual measurements from leaf sampling during summer of 2017 at the Mountains site, and interpolated to summer 2016 based on stem diameter.

2.7 HYDRUS-1D modeling

We used HYDRUS-1D version 4.16 (Simunek et al., 2005) to simulate water flow and root water uptake at both sites. HYDRUS is a modeling environment based on Richards' equation for variably saturated porous media. We used volumetric soil water content data from both sites to calibrate and validate the model. For the Mountains site, we used the period between 15 May and 12 August 2016, and for the Coastal Plain site, we used data collected between 1 May and 26 August 2016.

2.7.1 Boundary conditions and parameters

The parameters used for calibration, validation and simulation can be found in Tables 4.1, 4.2 and 4.3. Our boundary conditions for both sites were: 1) atmospheric upper boundary condition with surface layer of 1 cm; 2) free drainage for lower boundary; 3) no fluxes at other boundaries. Observed soil water content was used for initial conditions for every run of the model.

We estimated root distribution using minirhizotron data. HYDRUS-1D requires root distribution to be normalized between 0 and 1, 0 being no roots and 1 a maximum amount of roots (Lascano and Van Bavel, 1984). We assigned 1 to the depth in the soil profile that had the highest number of frames with roots, and extrapolated between 0 and 1 for the other depths. Our minirhizotron tubes sampled down to 47 cm. For modeling purposes, we assumed the permeable pavement to be homogeneous, and equivalent to a 10-cm thick layer of resin-bound pea gravel.

2.7.2 Model calibration

HYDRUS offers an inverse solution process to estimate the best fit for the hydraulic parameters, based on existing field data. Since we estimated α and n with the water retention curve, we ran the inverse solution to find the best fit for those two parameters. For the Mountains site we used volumetric soil water content field data from 15 May-17 June 2016, and for the Coastal Plain site from 1 May-12 June 2016.

An inverse simulation was run for each treatment. An average of the estimated parameters (α and n) across all four treatments was used for the validation phase (Table 4.3).

2.7.3 Model validation

Using the measured parameters and those obtained during the calibration process (Tables 4.1 and 4.3), we ran simulations for different treatments and compared them to the measured volumetric soil water content at 10-, 30- and 60-cm, to quantify model performance. For the Mountains site we used 17 June-12 August 2016, and for the Coastal Plain site 12 June-26 August 2016.

2.7.4 Model simulations

Once we had calibrated and validated the model, we ran simulations for different scenarios, using the same period of time as for validation. For the pavement simulations, we increased pavement thickness to 20 and 40 cm. For the soil texture simulations, we modified soil characteristics: at the Mountains site we assumed the entire soil profile was a clay horizon of equal texture to the actual 35-100-cm depth horizon, and at the Coastal Plain site we assumed the entire soil profile was a sandy horizon, equal to the actual 70-100-cm depth horizon. For the rooting depth simulation, we extended root depth from 47 cm to 80 cm, and assumed a normalized distribution of 0.65 and 0.8 for Tree-Paved and NoTree-Paved, respectively, at the Coastal Plain site, and 0.5 and 0.7 at the Mountains site.

2.8 Statistical analysis

We used the Nash-Sutcliffe Model Efficiency coefficient (NSE), Root Mean Square Error (RMSE), Relative Error (RE), and a coefficient of determination (R^2) to compare HYDRUS-1D simulations vs observed soil water content values for the validation models (Table 4.4):

$$NSE = 1 - \frac{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2}{\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y})^2} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} \quad (2)$$

$$RE = \frac{RMSE}{\bar{y}} \quad (3)$$

Where N is the number of observations, y_i is the observed value, $\hat{y}_i$ is the predicted value, and $\bar{y}_i$ is the mean observed value.

We assessed model performance based on Loague and Green (1991) and Yurtseven et al. (2013): excellent if the Relative Error (RE) for the field observed versus HYDRUS-predicted values is <10%; good if it is between 10-20%; fair 20-30%; and poor >30%.

3. Results and discussion

3.1 Model calibration and validation

We first ran HYDRUS-1D with the soil hydraulic parameters obtained with the pressure plate apparatus and water retention curve, but the predicted values for soil water content at 10-, 30-, and 60-cm below soil surface were not in good agreement with the observed field data. For example, at the Mountains, NSE value for 10-cm depth for NoTree-Paved was -92.99. Thus, we calibrated the model with the inverse solution using a subset of the field data for summer 2016, at both sites. Given that we used soil cores to estimate saturated water content and saturated hydraulic conductivity, we concentrated on optimizing α (air entry pressure parameter) and n (pore size distribution parameter) of the water retention curve. Also, a sensitivity analysis in another study showed α and n to be the most relevant parameters affecting the output of the simulation (Brunetti et al., 2016).

Having four different treatments resulted in four different sets of α and n parameters for each soil layer after calibration (Table 4.3). Thus, we averaged those four values to get a single set of α and n parameters for each soil layer to use in the validation. However, this may have resulted in suboptimal parameters for some treatments, for some soil layers. For example, at the Coastal Plain site, the HYDRUS-1D model did not converge during validation for the Tree-Paved treatment. Therefore, α and n for 0-25 cm soil layer, as well as α for the 25-70 cm soil layer, were tweaked slightly so that all treatments ran properly.

For the 0-25 cm soil depth, α was 0.005 cm^{-1} and n was 1.6; for the 25-70 cm soil depth, α was 0.02 cm^{-1}. The remainder of the parameters are those listed in Table 4.3. At the Mountains site there were no issues using the averaged parameters obtained from the calibration for the validation.

At the Mountains site, during validation, the best fit between observed and predicted values was closer to the soil surface, being better at 10- and 30 cm than at 60 cm. At this site, volumetric soil water content values at 60 cm measured with 5TM sensors were consistently lower than those predicted with HYDRUS-1D (Figures 4.3 and 4.4, and Table 4.4), and the validation RE values were very high. However, a visual comparison of the HYDRUS-1D data with the PR2 field data provided a better fit between model and observed values (Figures 4.3 and 4.4). This is possibly an artifact of the 5TM sensors' installation, when we augered the soil down to about 70 cm so we could install the sensors. Even though we carefully repacked the soil back in the augered hole, it appears that there might still have been a considerable density difference between the undisturbed soil, where the 5TM sensor prongs were placed, and the disturbed soil, where the back of the sensor was. The sampled soil volume by the 5TM sensor is a cylinder of approximately 10-cm high and 10-cm diameter. Therefore, half of the soil volume sampled by the sensor was in the undisturbed soil, and half in the disturbed soil. Furthermore, we observed at the end of the experiment that the walls of the augered hole where the sensors were placed were still mostly intact, further creating a barrier between the soil inside and outside of the hole used for sensor installation. At 10- and 30-cm depth, because of the lower clay content compared to 60-cm depth, this effect was not as evident. At the Coastal Plain site, we only used the continuous 5TM data for the validations, because of the time series sparsity of the PR2 data.

At the Coastal Plain site, the strong disagreements between HYDRUS-1D predictions and observed data at 10-cm depth for NoTree-Paved (Figure 4.5) might have been a result of root intrusion from nearby planted tree pits, which distorted the more homogenous soil water content pattern that is observed at 30- and 60-cm depths, and not lack of model fit. At 30 cm below soil surface at the Coastal Plain site, Tree-Paved and Tree-Unpaved field data initially showed little temporal variation (Figure 4.6). However, the model showed noticeable soil water content variations over time, possibly due to overestimation of soil water evaporation, as also noted by (Brunetti et al., 2016). Or this could have also been due to actual soil hydraulic conductivity values being lower than those we used in the model, thus showing an increased wetting front after the rainfall spike in early August. This could also be a result of HYDRUS-1D overestimating root water withdrawal earlier in the summer, based on the constant root distribution chosen for the validation, which depicts roots at 1 August 2016 and 28 July 2016, for the Mountains site and the Coastal plain site, respectively. Thus, by the end of July 2016, field data and HYDRUS-1D simulated soil water content at 30 cm below soil surface were more similar, suggesting that root presence at that depth was finally confirmed. This phenomenon can also be observed in August 2016 at the Mountains site (Figure 4.4), when field data values started to follow similar patterns as the model data.

At the Coastal Plain site, validation simulations were a very good fit to field data at 10-cm depth, except for NoTree-Paved treatment (Figures 4.5 and 4.6, and Table 4.4). As it happened at the Mountains site, model performance decreased deeper in the soil. However, considering that pavement effects on soil water content are generally more important right beneath the pavement (Morgenroth et al., 2013; de la Mota Daniel et al., 2018), the overall good model performance at 10 cm below the pavement suggests a high potential for using HYDRUS-1D to simulate soil water content under permeable pavements.

3.2 Model simulation: pavement thickness

Following model validation, we tested the model sensitivity to pavement thickness (Figures 4.7 and 4.8). At the Mountains site, with clay soil, increases in pavement thickness did not result in changes in simulated soil water content at any depth (Figure 4.7). This is consistent with findings in clay soil in Australia by Mullaney et al. (2015a), where increasing the sub-base thickness of pavement did not result in increased soil water content under the pavement. At the Coastal plain site, however, simulating a pavement thickness of 40 cm over coarser-textured soil, instead of the original 10 cm, resulted in simulated soil water content values higher at 10- and 30-cm soil depth during dry periods (Figure 4.8). This is also consistent with findings by Mullaney et al. (2015a), where a gravel base course increased soil water content near the soil surface over a sandy soil. This may be a consequence of the sharp change in texture between the clay soil and the pavement, which poses a discontinuity for upward water movement between soil and pavement, and soil water content is similar regardless of pavement thickness. However, with coarser-textured soil, reduced soil evaporation results in increased soil water content closer to soil surface, but dryer deeper in the soil, possible due to increased pavement storage.

3.3 Model simulation: root distribution

The minirhizotron tubes we installed for root monitoring only allowed us to observe roots down to 47 cm from soil surface. However, at harvest time we found roots down to at least 80 cm in the soil for some of the trees. Therefore, for simulation purposes we modified rooting depth in the model from 0-47-cm depth to 0-80-cm. At the Mountains site at 10- and 30-cm depth below the soil surface there was no difference in soil water content between the two root distributions for both treatments (Figure 4.9). At 60-cm depth below the soil surface, soil water content for a root distribution of 0-80 cm was lower than for the 0-47 cm root distribution in August 2016. For both treatments at the Coastal Plain site during half of the summer the soil water content was predicted higher at 10- and 30-cm depth for the deeper root distribution, while it was predicted as lower at 60-cm depth (Figure 4.10). Further work with root water uptake as well as with tree transpiration parameters is needed to fully assess the potential of HYDRUS-1D to predict root water uptake in tree-paved systems. Correct root distribution inputs in the model are fundamental for adequate simulation of soil water content, regardless of soil texture. Also, actual root depth distributions and densities may vary more in the soil profile than what we actually observed through minirhizotron monitoring. This may be an issue with many trees' root systems, coarser and less homogenous at the smaller scale than herbaceous' crops root systems, which may be easier to model at this scale.

3.4 Model simulation: soil texture

It is not uncommon in urban areas for a tree pit to not have distinct soil horizons due to backfill with brought-in soil. For this reason we ran simulations for both sites with the most extreme horizon characteristics extrapolated to the entire soil profile. Thus, we ran the Mountains site simulation as if the entire soil profile was the clayey Bt horizon, and the Coastal Plain site simulation as a sandy C horizon. For both Tree-Paved and NoTree-Paved treatments, the 10- and 30-cm depths at the Mountains site showed higher soil water content with the soil profile of a 100-cm clayey B horizon, while at the 60-cm water content was lower (Figure 4.11). The simulation did not converge for the two bare soil treatments (Tree-Unpaved and NoTree-Unpaved). For Tree-Paved, Tree-Unpaved, and NoTree-Unpaved treatments at the Coastal Plain site, soil water content was higher for the soil profile of a 100-cm sandy C horizon than for the original soil profile at all depths below soil surface (Figure 4.12). The simulation did not run for the NoTree-Paved treatment. The fact that those simulations did not run might be a result of using the initial conditions of the original soil horizon with the sandy or clayey characteristics for the entire soil profile. This may be a limitation for the applicability of HYDRUS-1D to use a calibrated model for a different scenario, and site-specific calibration may be needed.

3.5 Model uncertainties

In our experiment, we considered the pavement layer to be homogenous for parameterization and simulation purposes, as in Carbone et al. (2014), and extended the resin-bound pea gravel hydraulic characteristics to the entire pavement section. This may add uncertainty for extrapolating results to actual scenarios. However, a study with different types of permeable pavement designs and HYDRUS-2D simulations showed that the sub-base layers are less relevant for the infiltration capacity of the pavement, which is mostly determined by the hydraulic characteristics of the actual pavement layer, i.e., the resin-bound pea gravel in our experiment (Illgen et al., 2007). It appears that validations for NoTree-Paved are a better fit with a coarse soil texture (Coastal Plain) than with a finer-textured soil (Mountains), where HYDRUS-1D predicts higher soil water content fluctuations, not capturing the evaporative restriction caused by pavement. Another source of uncertainty is the parameters used to describe tree function in this system. However, despite having used the default Feddes' parameters for root water uptake based on deciduous fruit trees, simulated soil water content at 10- and 30-cm depth in the soil was in good agreement with observed data. This is important considering that most of the roots of *Platanus ×acerifolia* 'Bloodgood' were located at those depths in our experiment. In general we obtained the best validation results at the 10- cm depth, possibly due to a better soil parameterization at this depth. For example the 30-cm depth sensor is assumed to be in the same horizon as the 10-cm one, as this soil horizon is considered to reach a depth of 35 cm. However, it is possible that the actual soil characteristics at the location of the sensor may be different than at other locations in the experimental plot where we sampled the soil for characterization. This stresses the need for detailed soil parameter characterization where the sensors are placed for successful use of the model.

4. Conclusion

Overall, HYDRUS-1D modeling of soil water content in these tree pits at both sites is more successful for treatments with trees than without trees, regardless of pavement presence. At the Coastal Plain site the model is very responsive to rainfall events, overestimating infiltration. Better estimation of hydraulic conductivity may be needed. At the Mountains site, this enhanced infiltration effect is also apparent, but not as pronounced. It is also possible that at the Coastal Plain some results for unpaved treatments are confounded by root intrusion from nearby planted pits. It appears that the model provides better simulation of water loss due to tree transpiration than due to direct soil evaporation, providing predicted soil volumetric water content values consistently higher than observed values for treatments with no trees. Where roots are present, transpiration is a dominant factor in soil water flux, perhaps masking poor approximations for other factors influencing water flux. However, a more accurate root distribution input in the model may still be needed for better performance. The model is also more successful at simulating volumetric soil water content closer to the soil surface, even under permeable pavement, although a very good parameterization of the soil layers where the soil water content sensors are placed is fundamental for a good model performance. Thus, proper calibration and validation of the model might be a complex task for a typical streetscape design project. On the other hand, the characteristics and water content of the upper 30 cm of soil are decisive in regards to tree roots soil exploration. Thus, HYDRUS-1D may have potential to serve as a tool to predict soil water content in typical urban settings with coexisting pavement and tree roots, but further improvements in systems with no trees are needed.

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Figures and Tables

Figure 4.1. Plot layout at the Mountains site on 7 June 2016.

Figure 4.2. Detail of the layers forming the permeable pavement in this experiment: #57 crushed granite (bottom) and resin-bound pea gravel. Geotextile under the bottom layer not visible.

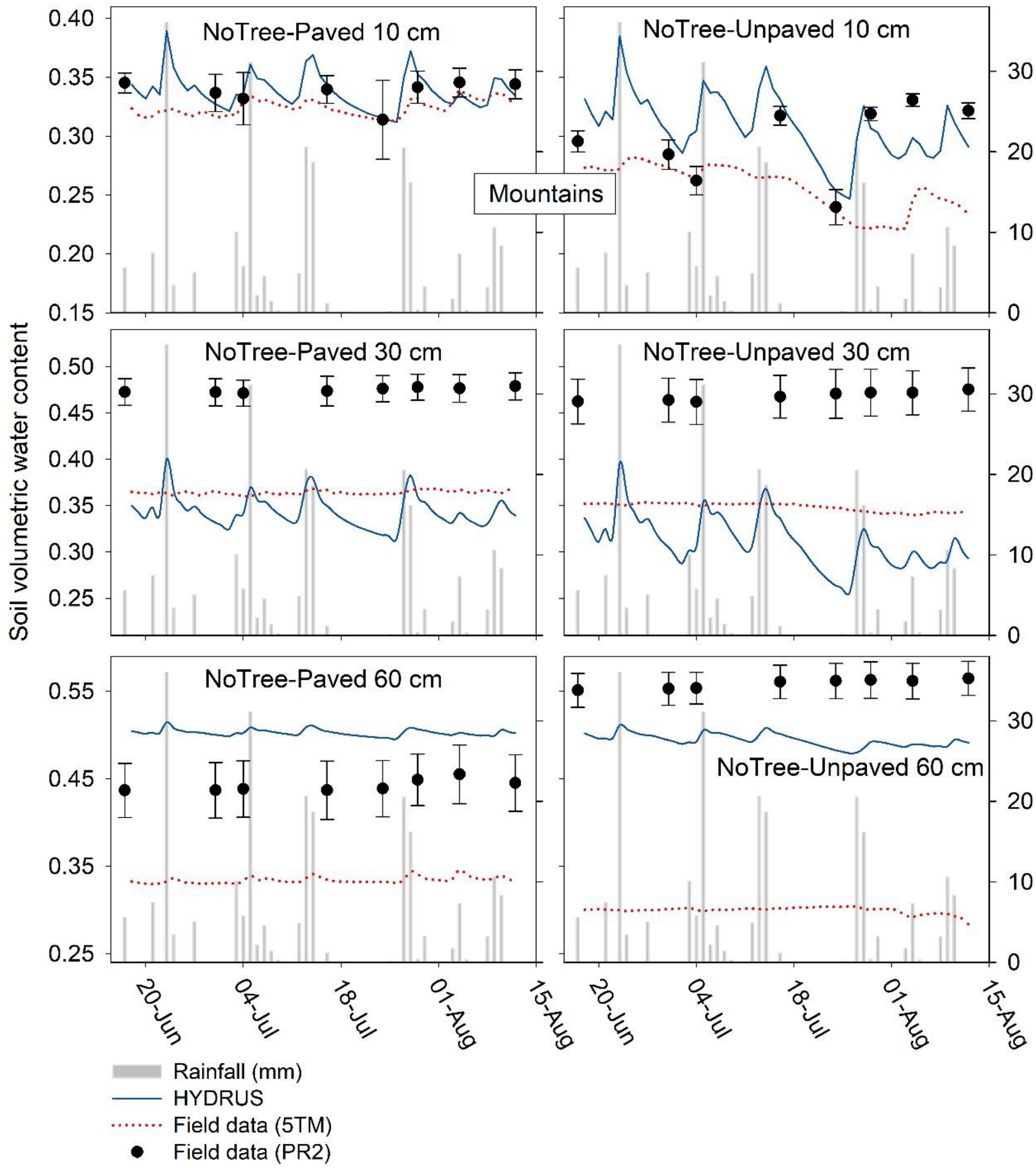

Figure 4.3. Observed (red dots and black circles) and simulated with HYDRUS (blue continuous line) soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits without tree, and with porous-permeable pavement (NoTree-Paved) or bare soil (NoTree-Unpaved), at the Mountains site. Field data 5TM dots represent observed daily average soil volumetric water content, n=1. Field data PR2 circles represent observed average soil volumetric water content on the dates represented, n=5. Error bars represent standard error of the mean. Gray bars show daily rainfall.

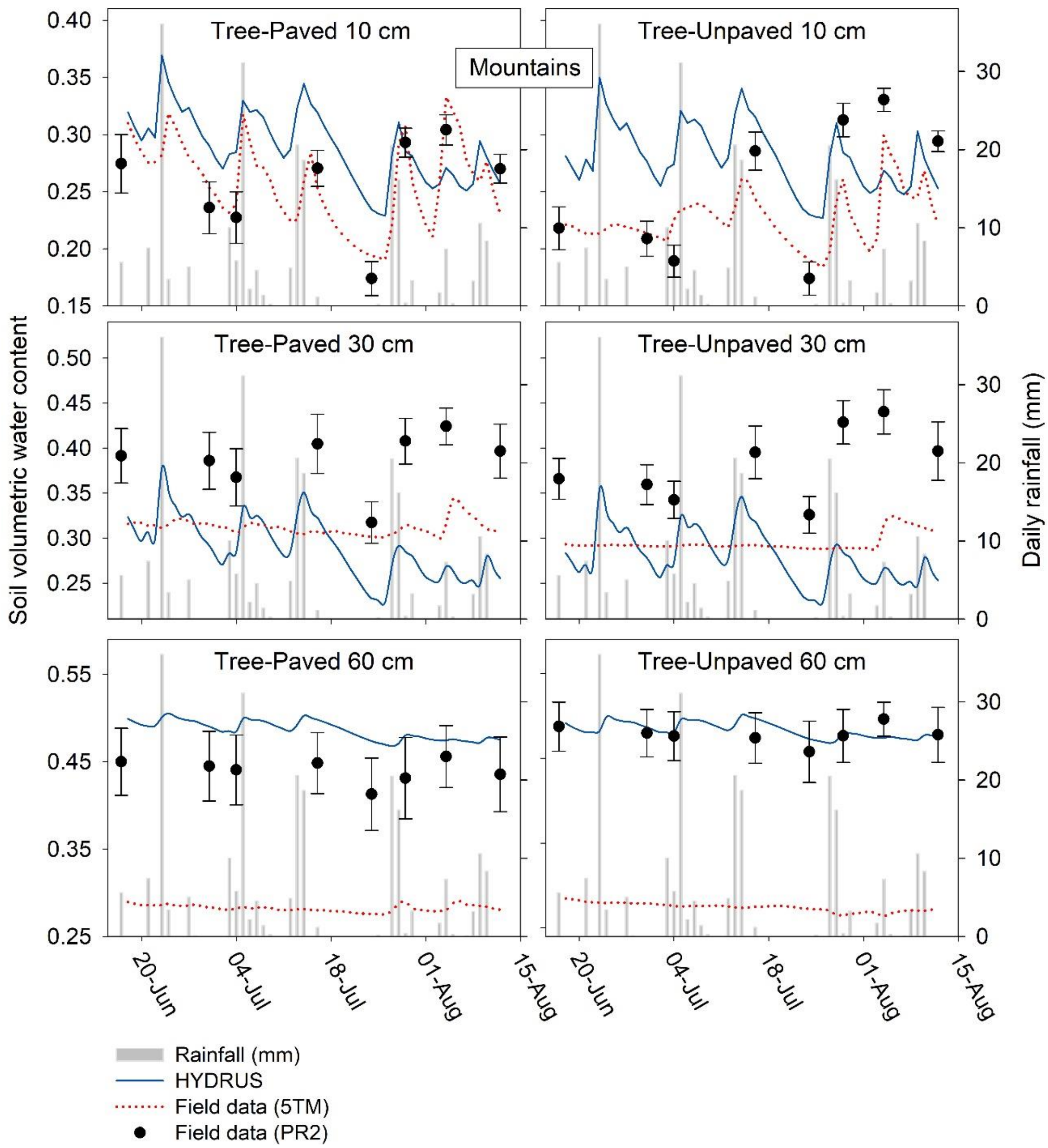

Figure 4.4. Observed (red dots and black circles) and simulated with HYDRUS (blue continuous line) soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* ‘Bloodgood’, and with porous-permeable pavement (Tree-Paved) or bare soil (Tree-Unpaved), at the Mountains site. Field data 5TM dots represent observed daily average soil volumetric water content, n=1. Field data PR2 circles represent observed average soil volumetric water content on the dates represented, n=5. Error bars represent standard error of the mean. Gray bars show daily rainfall.

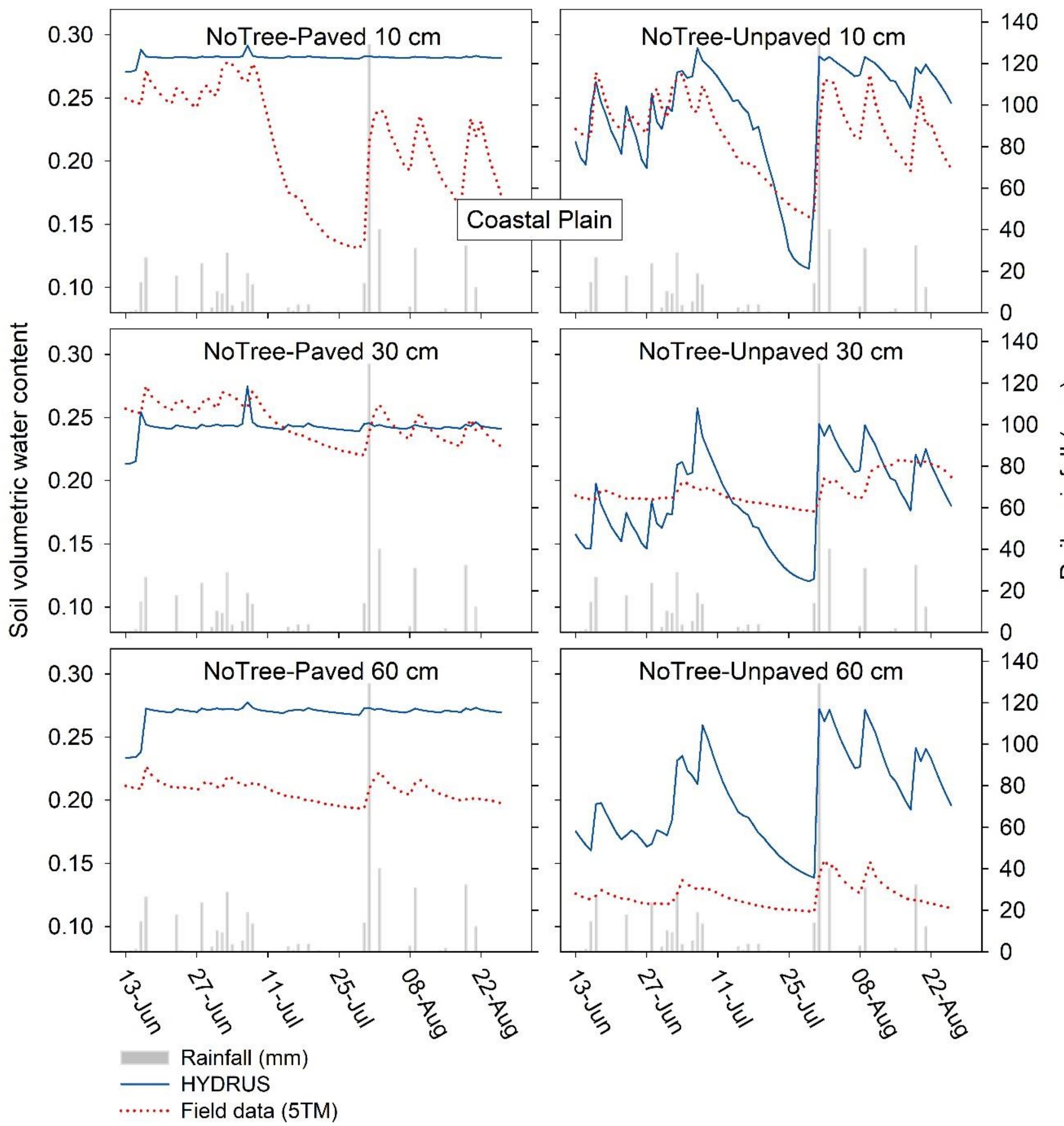

Figure 4.5. Observed (red dots) and simulated with HYDRUS (blue continuous line) soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits without tree, and with porous-permeable pavement (NoTree-Paved) or bare soil (NoTree-Unpaved), at the Coastal Plain site. Field data 5TM dots represent observed daily average soil volumetric water content, n=1. Gray bars show daily rainfall.

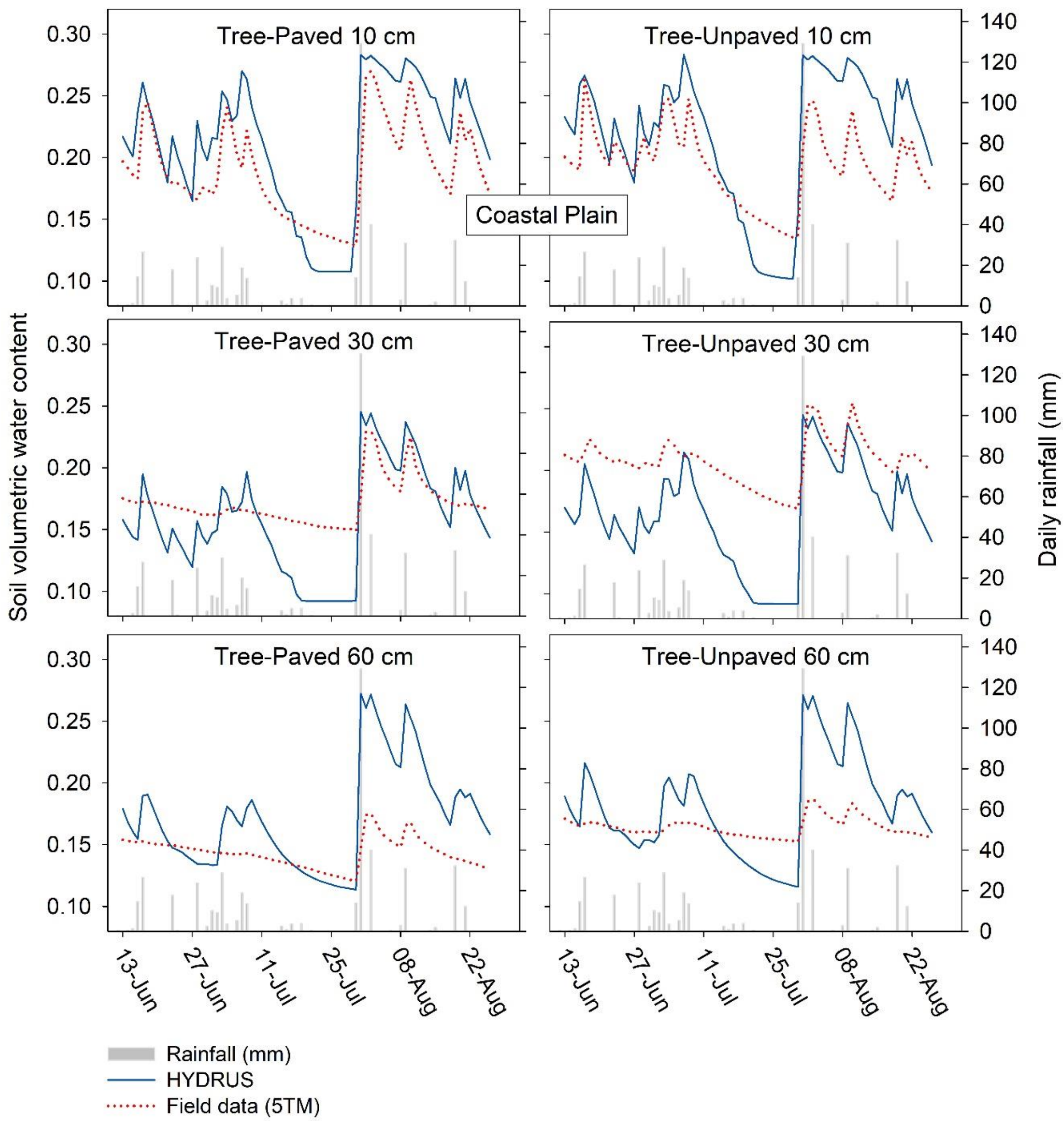

Figure 4.6. Observed (red dots) and simulated with HYDRUS (blue continuous line) soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* ‘Bloodgood’, and with porous-permeable pavement (Tree-Paved) or bare soil (Tree-Unpaved), at the Coastal Plain site. Field data 5TM dots represent observed daily average soil volumetric water content, n=1. Gray bars show daily rainfall.

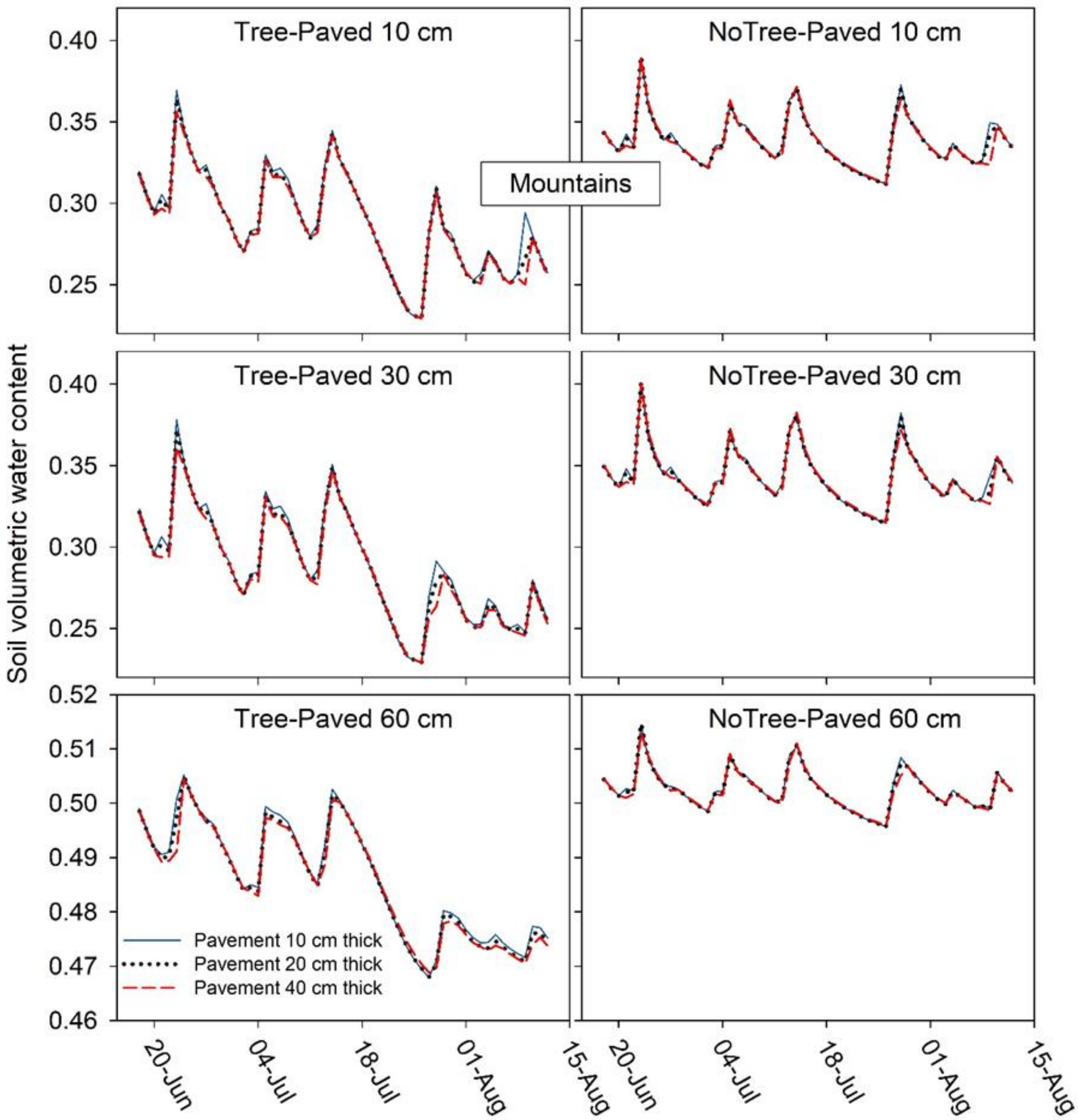

Figure 4.7. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* 'Bloodgood' and covered with porous-permeable pavement (Tree-Paved), or without tree and covered with pavement (NoTree-Paved), at the Mountains site. Simulations presented are for 10-cm thick pavement (blue continuous line), 20-cm thick pavement (black dotted line), and 40-cm thick pavement (red dashed line).

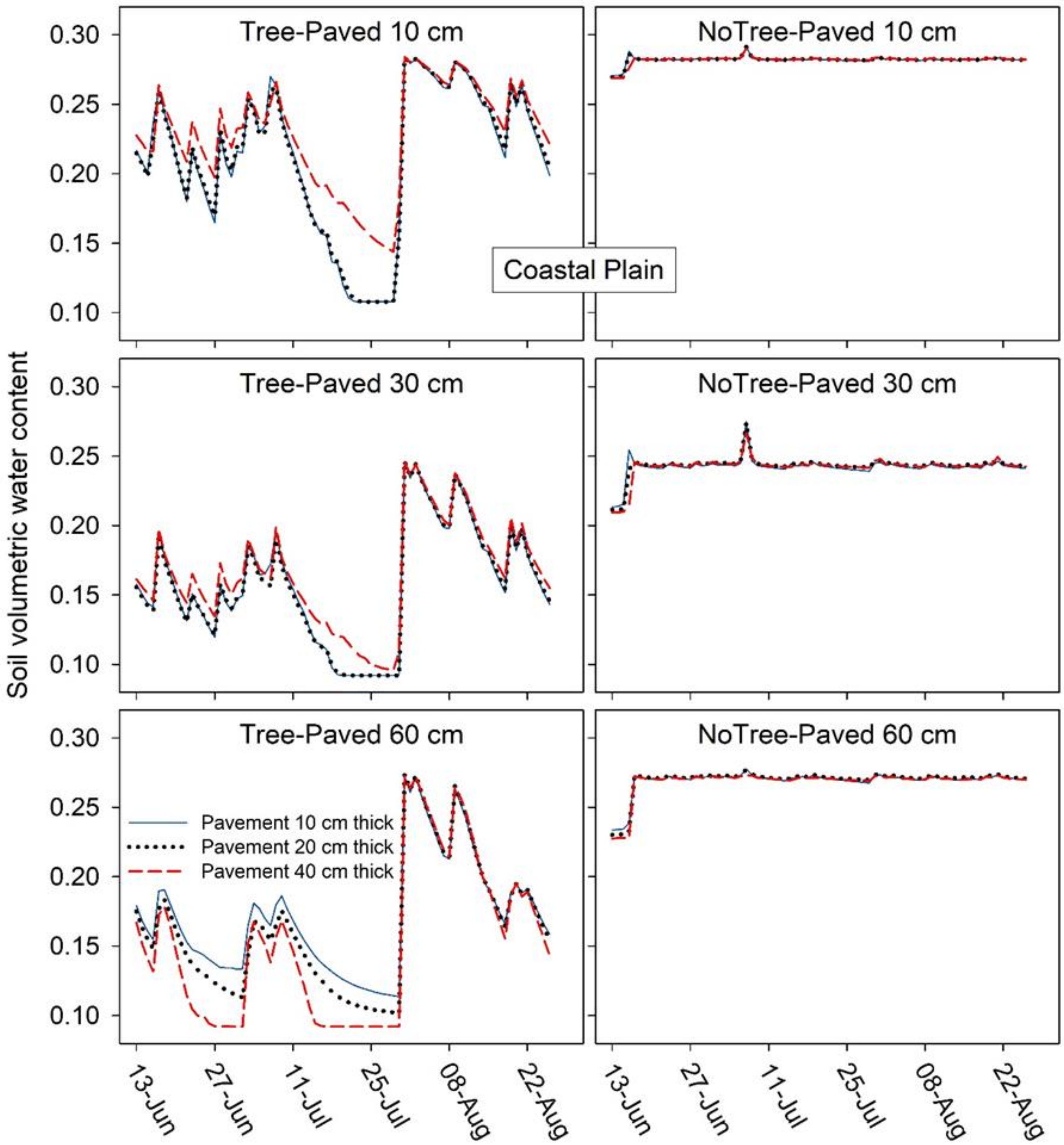

Figure 4.8. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* 'Bloodgood' and covered with porous-permeable pavement (Tree-Paved), or without tree and covered with pavement (NoTree-Paved), at the Coastal Plain site. Simulations presented are for 10-cm thick pavement (blue continuous line), 20-cm thick pavement (black dotted line), and 40-cm thick pavement (red dashed line).

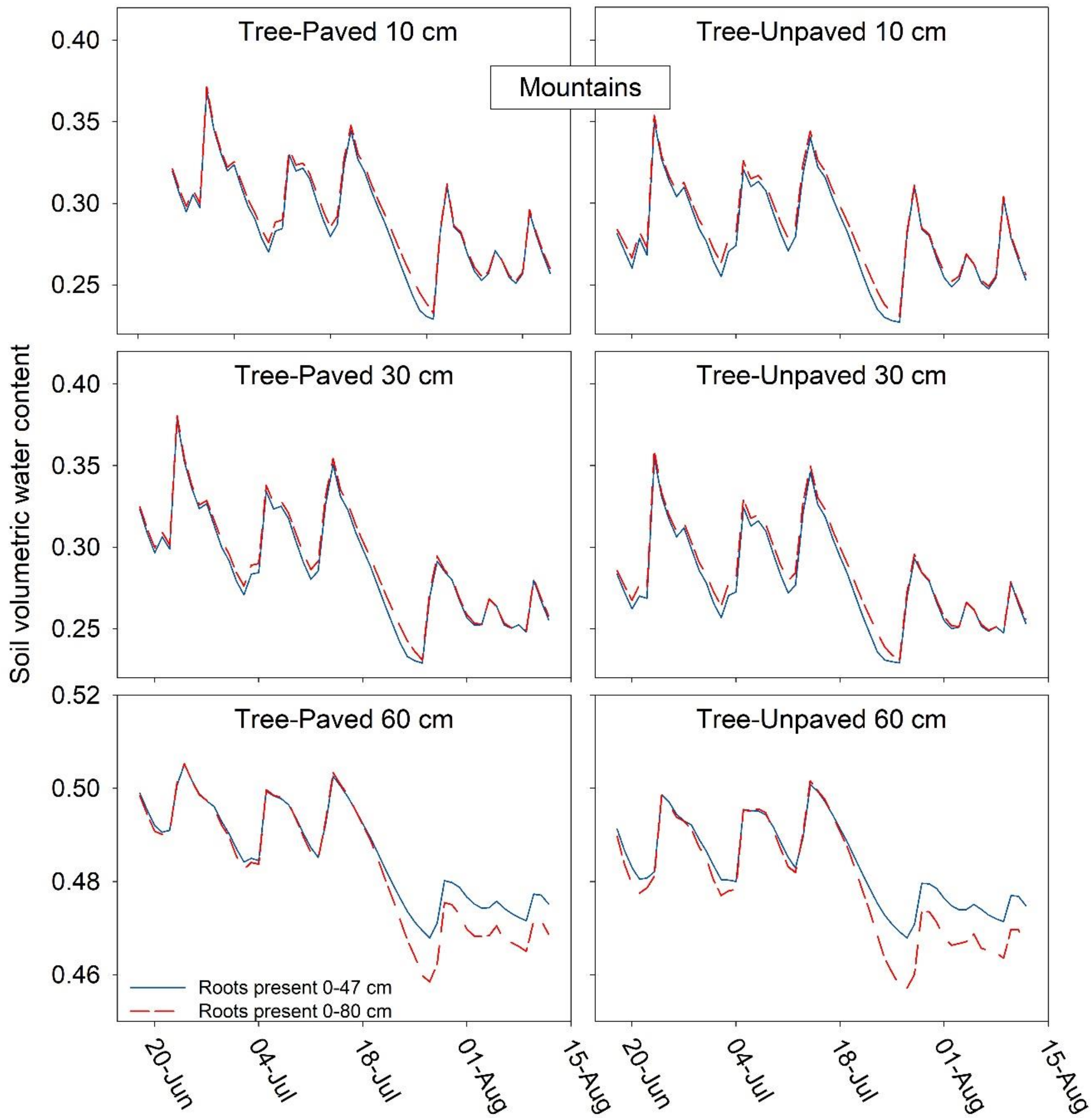

Figure 4.9. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* ‘Bloodgood’, covered with porous-permeable pavement (Tree-Paved), or without pavement (Tree-Unpaved), at the Mountains site. Simulations presented are for root presence from soil surface to a 47-cm depth (blue continuous line) and for root presence from soil surface to 80-cm depth (red dashed line).

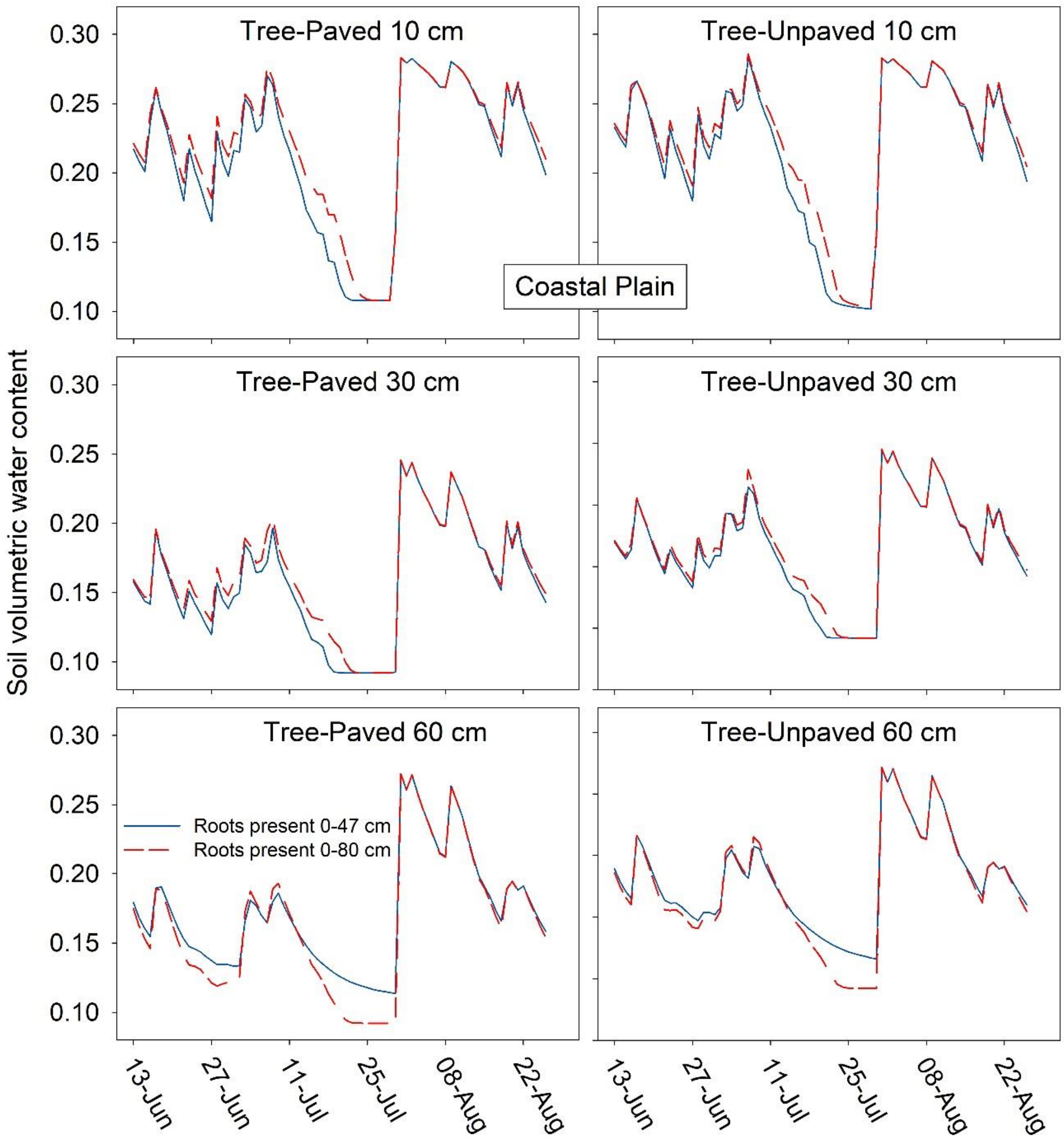

Figure 4.10. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with Platanus ×acerifolia 'Bloodgood', covered with porous-permeable pavement (Tree-Paved), or without pavement (Tree-Unpaved), at the Coastal Plain site. Simulations presented are for root presence from soil surface to a 47-cm depth (blue continuous line) and for root presence from soil surface to 80-cm depth (red dashed line).

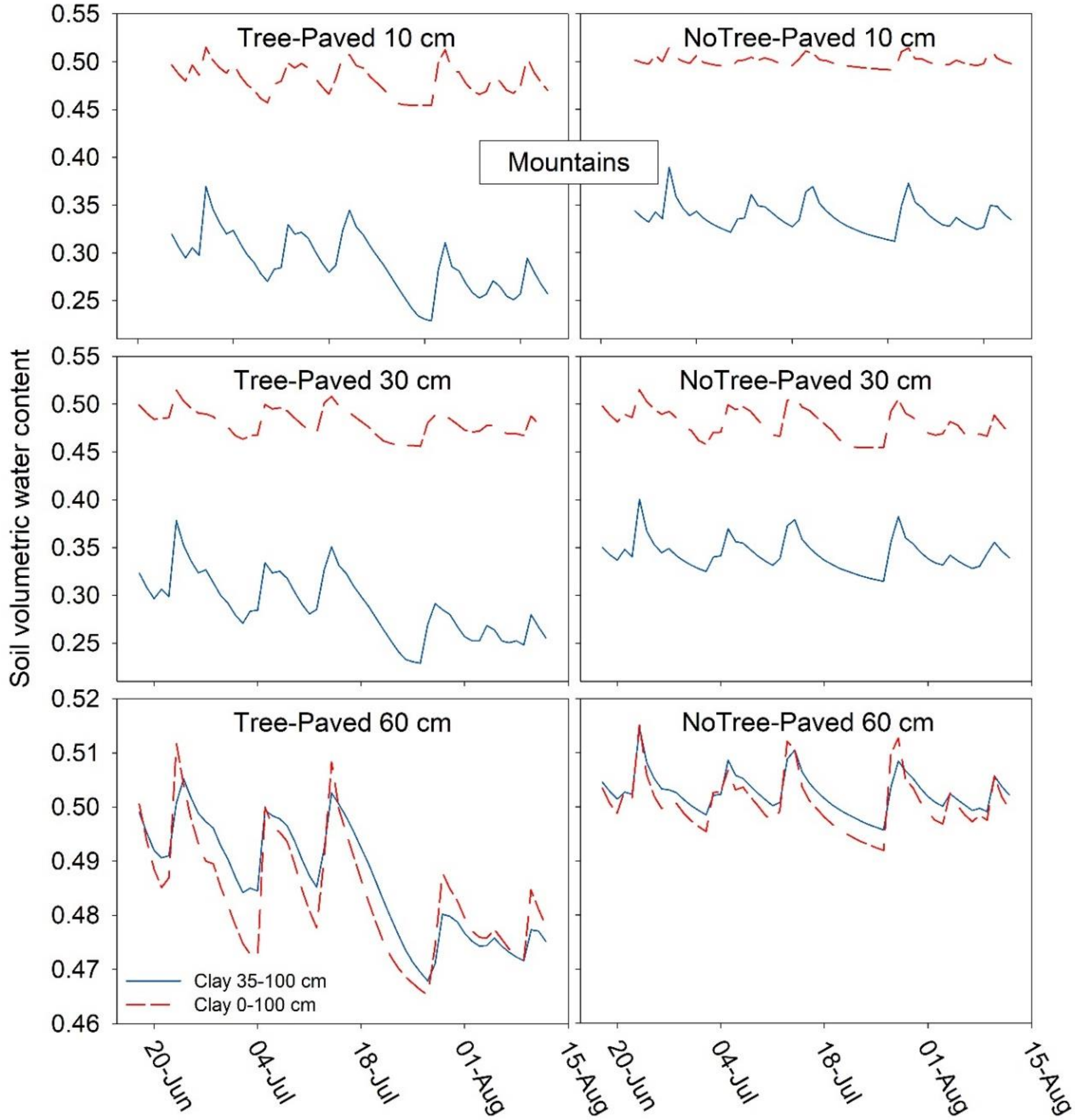

Figure 4.11. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits covered with porous-permeable pavement, and either planted with *Platanus ×acerifolia* ‘Bloodgood’ (Tree-Paved), or without tree (NoTree-Paved), at the Mountains site. Simulations presented are for the original Mountains site soil profile, with 47% clay content between 35-100 cm beneath a silt-loam (blue continuous line), and for a presumed soil profile with 47% clay content between 0 -100 cm (red dashed line).

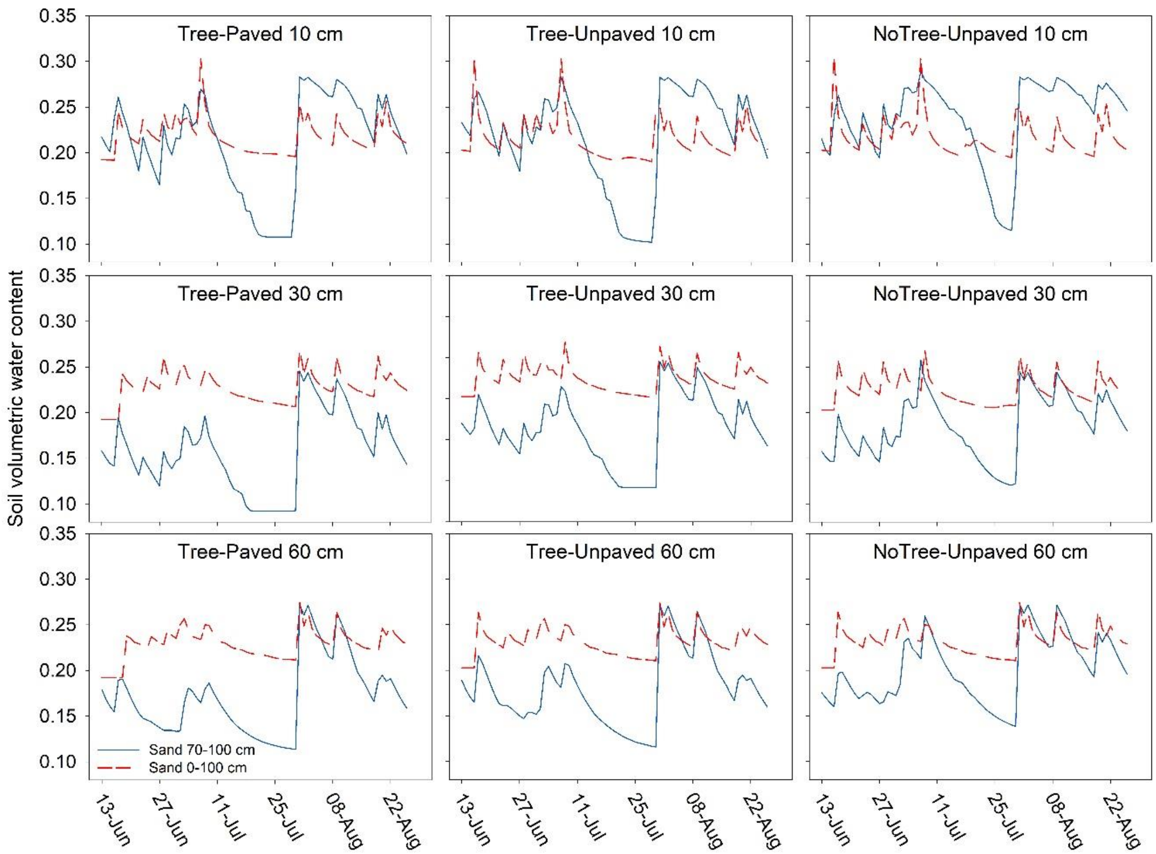

Figure 4.12. HYDRUS simulated soil volumetric water content at 10-, 30-, and 60-cm below soil surface for 1 m^2 tree pits planted with *Platanus ×acerifolia* 'Bloodgood' and covered with porous-permeable pavement (Tree-Paved), or without pavement (Tree-Unpaved), or without tree and without pavement (NoTree-Unpaved) at the Coastal Plain site. Simulations presented are for the Coastal Plain site original soil profile, where the C horizon (70-100 cm, 95% sand) is beneath a loam (blue continuous line), and for a presumed soil that is 95% sand from 0-100 cm (red dashed line).

Table 4.1. Measured and estimated soil properties for the Coastal Plain and the Mountains site.

Depth (cm)	Textural fractions			Bulk density (g cm^{-1})		K_s (cm hr^{-1})		Θ_s		Θ_r[‡]	α[‡]	*n*[‡]	*l*[†]
	Sand (%)	Silt (%)	Clay (%)	Mean	SE	Mean	SE	Mean	SE				
Coastal Plain													
0-25	62.94	29.32	7.74	1.59	0.04	13.16	3.52	29.34	1.98	0.085	0.0004	1.800	0.5
25-70	78.70	12.02	9.26	1.58	0.03	5.33	1.39	27.92	3.15	0.076	0.010	1.847	0.5
70-100	94.36	1.70	3.90	1.42	0.01	368.29	59.50	32.95	1.54	0.020	14.545	1.196	0.5
Mountains													
0-35	23.06	63.46	13.51	1.37	0.01	34.4	9.15	40.54	0.46	0.195	0.018	1.497	0.5
35-100	12.08	40.98	46.96	1.21	0.03	6.22	2.08	51.54	1.22	0.329	0.005	2.187	0.5
Pavement	-	-	-	1.39	-	3600[¶]	-	0.26	-	0.016[¶]	0.145[¶]	2.680[¶]	0.5

[‡] estimated from water retention curve [¶] estimated from gravel and sand values † default value from HYDRUS

Table 4.2. Parameters used in the HYDRUS simulations.

Parameters and variables	**HYDRUS inputs**
Main processes	Water flow Root water uptake (Tree-Paved and Tree-Unpaved only)
Length units	cm
Decline from vertical axes	Vertical
Depth of soil profile	Tree-Paved and NoTree-Paved: 110 cm Tree-Unpaved and NoTree-Unpaved: 100 cm
Number of materials and layers in the soil	*Mountains site* Tree-Paved and NoTree-Paved: 3 Tree-Unpaved and NoTree-Unpaved: 2 *Coastal Plain site* Tree-Paved and NoTree-Paved: 4 Tree-Unpaved and NoTree-Unpaved: 3
Time units	Hours
Time period	*Calibration* Mountains site: 15 May - 17 June 2016 Coastal Plain site: 1 May -12 June 2016 *Validation* Mountains site: 17 June – 12 August 2016 Coastal Plain site: 12 June – 26 August 2016
Initial time step	0.024
Minimum time step	0.00024
Maximum time step	120
Number of time-variable boundary conditions and meteorological records (in hours)	*Calibration* Mountains site: 816 Coastal Plain site: 1032 *Validation* Mountains site: 1345 Coastal Plain site: 1801
Maximum number of iterations	10
Water content tolerance	0.001
Pressure head tolerance	1
Hydraulic model	Single porosity model, van Genuchten - Mualem
Hysteresis	No hysteresis
Soil hydraulic parameters	See Tables 4.1 and 4.3
Upper boundary condition	Atmospheric BC with surface layer, max 1 cm
Lower boundary condition	Free drainage
Initial conditions	In pressure head
Water uptake reduction model	Feddes
Solute stress model	No solute stress
Critical stress index for water uptake	0.6

Feddes' parameters	Default for deciduous fruit: PO (cm) -10 POpt (cm) -25 P2H (cm) -500 P2L (cm) -800 P3 (cm) -8000 r2H (cm/hr) 0.021 r2L (cm/hour) 0.0042
Radiation and cloudiness	Solar radiation
Geographical and meteorological parameters	Mountains site Latitude: 37ºN Altitude: 622 m Coastal Plain site Latitude: 36ºN Altitude: 9 m
Crop data	Constant growth Crop height: 450 cm Albedo: 0.23 (default) Leaf area index: 4.5 (Tree-Paved) and 3.5 (Tree-Unpaved) Root depth: 47 cm
Radiation extinction	0.463
Interception constant	1.1
Root distribution	Proportion of roots 0- 47 cm
Depth of observational nodes	10-, 30-, and 60- cm

Table 4.3. Fitted hydraulic parameters and confidence intervals (CI) obtained from the HYDRUS inverse solution, for the Coastal Plain and Mountains sites.

Depth (cm)	Treatment	*α*	*n*
		Value ± CI	Value ± CI
Coastal Plain			
0-25	NoTree-Paved	0.0097 ± 0.0058	1.41 ± 4.97
	NoTree-Unpaved	0.011 ± 0.0037	1.41 ± 2.28
	Tree-Paved	0.004 ± 0.0012	2.0 ± 0.69
	Tree-Unpaved	0.0054 ± 0.0030	1.52 ± 2.27
	Mean	0.0075	1.59
25-70	NoTree-Paved	0.015 ± 0.0041	1.5 ± 1.46
	NoTree-Unpaved	0.035 ± 0.0116	1.5 ± 0.97
	Tree-Paved	0.018 ± 0.0034	1.5 ± 0.44
	Tree-Unpaved	0.019 ± 0.0121	1.5 ± 1.54
	Mean	0.022	1.50
70-100	NoTree-Paved	14.545 ± 33.95	1.19 ± 0.12
	NoTree-Unpaved	14.545 ± 62.62	1.10 ± 0.18
	Tree-Paved	14.545 ± 38.46	1.10 ± 0.12
	Tree-Unpaved	14.545 ± 51.77	1.147 ± 0.13
	Mean	14.55	1.13
Mountains			
0-35	NoTree-Paved	0.012 ± 0.0189	1.39 ± 0.33
	NoTree-Unpaved	0.02 ± 0.0398	1.39 ± 0.27
	Tree-Paved	0.012 ± 0.0144	1.39 ± 0.19
	Tree-Unpaved	0.012 ± 0.0324	1.39 ± 0.22
	Mean	0.014	1.39
35-100	NoTree-Paved	0.0108 ± 0.0107	1.09 ± 0.50
	NoTree-Unpaved	0.013 ± 0.0163	1.09 ± 0.83
	Tree-Paved	0.0108 ± 0.0047	1.09 ± 0.32
	Tree-Unpaved	0.005 ± 0.0087	1.09 ± 0.82
	Mean	0.0099	1.09

Table 4.4. Goodness of fit measures for the field-observed vs HYDRUS-predicted soil water content values at different soil depths. The validation period for the Coastal Plain site is 12 June-26 August 2016 and for the Mountains site is 17 June-12 August 2016.

Treatment	10 cm				30 cm				60 cm			
	NSE	RMSD	RE	R^2	NSE	RMSD	RE	R^2	NSE	RMSD	RE	R^2
Coastal Plain												
NoTree-Paved	-2.40	0.082	0.38	0.0005	-0.25	0.016	0.07	0.003	-71.03	0.06	0.31	0.0003
NoTree-Unpaved	-0.25	0.033	0.15	0.56	-5.51	0.030	0.16	0.37	-75.69	0.08	0.66	0.66
Tree-Paved	0.11	0.035	0.18	0.78	-2.33	0.033	0.19	0.71	-12.71	0.04	0.31	0.62
Tree-Unpaved	-0.82	0.041	0.21	0.70	-6.54	0.051	0.25	0.80	-21.48	0.04	0.22	0.81
Mountains												
NoTree-Paved	-6.82	0.019	0.06	0.21	-166.73	0.026	0.07	0.06	-2232.02	0.17	0.51	0.21
NoTree-Unpaved	-7.23	0.056	0.22	0.36	-103.59	0.046	0.13	0.25	-2743.18	0.19	0.65	7E-05
Tree-Paved	0.45	0.046	0.22	0.31	-7.88	0.041	0.14	0.01	-1708.91	0.20	0.73	0.08
Tree-Unpaved	-5.98	0.062	0.27	0.12	-13.94	0.036	0.12	0.05	-1868.98	0.21	0.76	0.35

Chapter 5
Summary and Conclusions

Permeable pavement installations are becoming common practice in urban streetscapes. Furthermore, tree pits are also being covered with these materials, influencing tree growth and water fate in the soil, thus affecting ecosystem service provision by trees. Our data showed that resin-bound gravel pavement installations in tree pits altered soil water content and temperature patterns, affecting tree growth and root development. Analysis of water inputs and outputs of the tree pit system and the entire experimental plot also demonstrated the importance of trees in the urban water balance. Where trees were present, transpiration dominated water output. We would expect as trees mature and roots more fully explore the landscape below ground, transpiration will play an increasingly major role as an output in paved environments. Our study with the HYDRUS-1D modeling environment also showed some potential for using this model as a tool to predict soil water movement and possibly tree root growth under permeable pavements, with the goal of improving tree-pavement design and installation in urban areas.

Porous-permeable pavement effects on tree growth and root development

We evaluated the effect of resin-bound gravel porous-permeable pavement installations in tree pits on the growth, establishment and root depth distribution of *Platanus ×acerifolia* 'Bloodgood' trees. Our study shows that trees in paved tree pits produced roots sooner after transplanting, and also developed larger roots systems. This pavement effect on tree root development is probably a combination of various factors: an insulating effect due to pavement, which increased soil temperature, extending the root growing season earlier in spring and later in fall. And also due to the increased soil water content at the soil surface, as observed by Morgenroth and Buchan (2009), where many of the roots developed. At the same time, trees in paved pits also grew larger, with increased stem diameter and canopy width and height compared to those in unpaved pits. Presumably this is due to these same below-ground conditions. This increased soil water content under pavement compared to unpaved pits resulted in shallower roots in our study, which is a well-known issue when growing trees in paved areas. Root depth distribution is of considerable concern to cities, since shallow roots can lead to pavement damage, with great cost to cities and towns in sidewalk repair and associated litigation (McPherson, 2000). The development stage of the trees is probably also relevant to the extent of the tree pit-covering-pavement effects on tree growth, particularly on root depth distribution. In our study we used very young trees that initially had all their roots within the tree pit, under the pavement in the case of paved pits. As roots grew out of the tree pits, under the impermeable section of the experimental plot (as they would in a conventional sidewalk design), all roots were under the same conditions, impermeable pavement. Also, as noted by Volder et al. (2009), retrofitting permeable pavement around mature, established trees may not have any effect on tree growth. This is of importance for street renovation projects when planners and administrators often need to decide between preserving existing trees or planting new ones. Our findings suggest it is the interaction of pavement design, climate, and tree development stage that dictates the outcome of pavement installation in tree pits, especially in regards to soil exploration by roots. Furthermore, as trees mature, the material beyond the tree pit will exert greater influence on further root growth and associated effects on tree physiology.

A future research area is the interaction of various permeable pavement designs (e.g., thicknesses, materials) with the soil type beneath it. In our experiment, at both sites, the existing soil was considered prime agricultural soil, and having low compaction. However, urban soils, and particularly those under pavement, are frequently very compacted so they can bear the load of pavement and vehicles. To remediate this issue, structural soils (soil mixes engineered to be load-bearing while still allowing root growth) and cells (modular vault systems that allow uncompacted soil to be placed below pavement) are used to provide optimal soil volume for root development (Grabosky and Bassuk, 1995; Smiley et al., 2006). It is therefore of interest to understand how soil water moves in a greater variety of tree pit-pavement-soil systems and how roots develop in such installations under a variety of climates.

The resin-bound gravel pavement used in our experiment had a low albedo, resulting in soil warming in paved pits, compared to unpaved ones. For example, we observed at the Mountains site that snow melted faster in paved tree pits. It would also be interesting to investigate the effect of white or light-colored pavement on soil water and temperature, and on tree root growth, and what the implications of these pavement color selections would be for trees in cold and warm climates, and in dry and humid ones.

As a final thought, tree species almost certainly plays a role in how tree roots explore soil beneath pavements. We used *Platanus* ×*acerifolia* 'Bloodgood' trees, a very common urban tree in temperate climate areas of the world, and also very fast growing under the soil and climate conditions of both of our experimental sites. However, other species that are, for example, slower growing like *Ginkgo biloba*, *Styphnolobium japonicum* and *Tilia cordata*, might perform differently under permeable pavements. Understanding their response to permeable pavement installations would add more basis to extrapolate results to other scenarios. Also, the majority of the research investigating the below-ground attributes of streetscapes has been conducted in temperate climates. Thus these interactions among tree species, pavement design and climate need to also be evaluated with tropical tree species in climates with no distinct winter season.

Trees and permeable pavements in the urban water balance

Dense urban landscapes are often dominated by impervious surfaces. In these areas, stormwater runoff becomes an important environmental concern due to pollutant transport and increased peak flows in streams. Trees in tree pits can be considered part of decentralized stormwater control measures, having a relevant role in the urban water balance. In our study, even young trees dominated the water balance through transpiration during the leaf-on period, especially in the paved tree pits that had larger trees and reduced direct soil evaporation due to soil being covered with pavement. For example, sap flow measurements over one week when trees were fully leafed showed that tree transpiration was between 33% and 64% of total water outputs, for Tree-Unpaved and Tree-Paved, respectively. This means that transpiration was more than 100% of total water inputs, showing that the combination of trees and permeable pavements could help with stormwater management by increasing water storage potential, through tree transpiration, water infiltration and permeable pavement storage, in urban areas. However, since the tree pits in our experiment were designed to prevent runoff from adjacent surface into the pits, future studies should aim at quantifying tree pit functioning under scenarios where a portion of the stormwater runoff actually flows into the tree pits.

Our study comprised a small period of time when trees had leaves on, and the leaf-off period can be half of the year in many temperate-climate areas. A future approach might be to quantify the tree pit water balance at a yearly timeframe, including the leaf-off periods, when tree transpiration is greatly reduced, and tree contributions to stormwater capturing are reduced to stem interception and increased water infiltration and deep drainage mediated by roots. In other parts of the world with an arid climate, however, water conservation may be a greater concern than stormwater management. It would be of interest to quantify the tree pit water balance in these areas, with very different tree transpiration regimes and very high evaporative demand. Furthermore, in very dry climates, the condensation and distillation processes that increase soil water content directly under pavement might be less relevant, potentially driving different tree root depth distributions than in humid climates. These site-specific circumstances should be considered in future streetscape planning and site renovation.

The overestimation discrepancies found in our study in change in storage in tree pits without trees are likely due to tree root soil colonization beyond the tree pit boundaries, entering the pits with no trees. Despite the source of error it created in the quantification of the water balance at the tree pit scale, it also provided understanding of a more typical urban streetscape scenario, where roots are in the pits and beyond, under the adjacent pavement. However, an experiment setup that allows full control of the soil available for root exploration, and the inputs and outputs into each tree pit, may be a good complementary study to ours. For example, a controlled environment study with trees growing in containers on lysimeters and simulated rainfall may be valuable to further understand tree and pavement contributions to the urban water balance. Furthermore, this setup may be useful to study the transpiration of trees with greater stomatal control than *Platanus* ×*acerifolia* ‘Bloodgood’, as well as testing pavement with different albedo values to better understand the role of pavement characteristics on soil water evaporation.

HYDRUS-1D modeling of soil water in combined paved-planted systems

Modeling can provide important insight into processes of which we need better understanding, in order to predict outcomes and inform policy. As sustainability concerns rise with expanding urban areas, integrating trees and infrastructure in the urban landscape has garnered interest as a means to mitigate environmental issues that derive from dense urbanization, including stormwater runoff, urban heat island effects, and human wellbeing. In this arena tree pit design may have an important role in increasing the performance of the combination of trees and permeable pavements as nature-based solutions in streetscapes. Thus, modeling soil water content in permeable pavement installations with trees may be a useful tool to inform municipal codes and urban planning.

In our study, we used HYDRUS-1D to model soil water content in tree pits. The air entry pressure parameter α and the pore size distribution parameter n obtained from the water retention curve did not provide simulations with a close fit to field data. Therefore we calibrated the model with the inverse solution available in HYDRUS-1D and with part of the observational data from soil water content monitoring at the experimental sites. For model validation, HYDRUS-1D-predicted soil water content values were closer to the observed field data for planted pits, at both sites. Also, this was so for both paved and unpaved tree pits. At the same time, the model-predicted values for soil water content fit the field data better at 10 cm below soil surface, also under permeable pavement, than deeper in the soil. Finding the best parameters for our model had the added complexity of having four different treatments. This decreased fit during validation, because of the averaged parameter values used. Creating a catalog of hydraulic parameters for a variety of soil-pavement-tree root scenarios based on experimental data at different sites may be useful to increase the potential of HYDRUS-1D as a tool to improve streetscape design. However, this would most likely not prevent the need for model calibration, reducing model applicability.

On the other hand, the good validation results for planted tree pits suggests that the default root water uptake parameters for trees may suffice for water extraction prediction by a variety of tree species, although a parameter catalog more applicable to urban trees would be desirable. Future work should concentrate on testing the model performance on structural soils and other manufactured media and structures for tree growth in urban sites. Overall, given the good modeling results in the upper 30 cm of soil, there is potential to use HYDRUS-1D as a tool to improve design details, and to develop standards for permeable pavement design. It would be of interest, for example, to explore HYDRUS modeling with permeable pavements over saturated base courses, which often result from conventional soil compaction under pavement at urban sites.

In summary, this work investigated some of the implications of permeable pavement installation in regards to tree development in urban areas, and provides insight into using nature-based solutions for the integration of trees in cities. Further work is needed to understand how trees, street infrastructure, urban soils and stormwater interconnect. However, a key factor for tree pit and streetscape design that maximizes tree growth, and stormwater runoff mitigation, and that reduces tree-infrastructure conflicts, is the need for engineers, planners and administrations to perceive trees as part of the urban infrastructure itself, and not just as an aesthetical amenity.

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Appendix 1

Supplemental Figures from Chapter 2

Fig. S1. Photograph of roots directly under the pavement for a tree in PP at the Coastal plain site at harvest time (October 14, 2016).

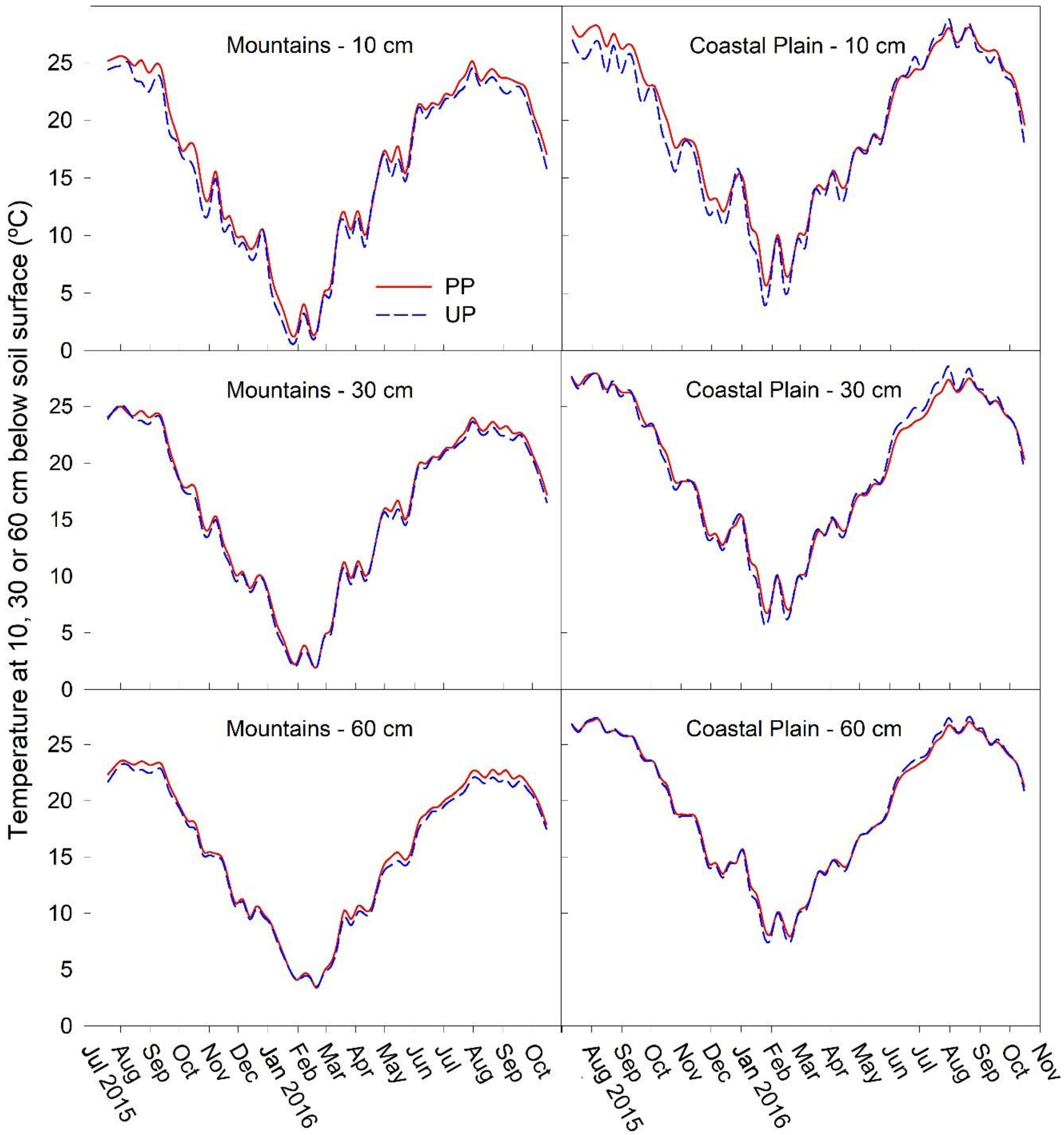

Fig. S2. Change in weekly average soil temperature at 10, 30, and 60 cm below soil surface for simulated tree pits (1 m2 each) planted with *Platanus ×acerifolia* 'Bloodgood', with porous pavement and bare soil treatments, at two experiment locations, n=1.

Fig. S3. Photographs of a tree in PP (left) and a tree in UP treatments at the Coastal Plain site in summer of the first growing season (13 August 2015).

Fig. S4. Photographs of the same two trees as in Fig. S3 - PP (left) and UP - at the Coastal Plain site in summer of the second growing season (28 July 2016).

Fig. S5. Photographs of finished surface for PP (left) and UP tree pits showing albedo contrast between treatments at the Mountain site.