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When green infrastructure turns grey: implications of overdesign for plant water stress

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ABSTRACT

Overdesign is a common strategy used by green infrastructure (GI) designers to account for unexpected performance loss, but such a strategy can create undesirable plant responses if it decreases water availability. The seasonal and event-based stomatal conductance data of two woody plant species in a green infrastructure (GI) was analyzed. The GI is a tree trench composed of five tree pits (each one was planted with a tree) in an infiltration bed. Runoff collected from the street was supplied to the bottom of the infiltration bed, although the system never filled completely indicating there was capacity for more runoff than what was observed over 3 years and the infiltration bed was overdesigned. Between the two tree species, evidence suggested that the root system of London plane spread beyond the boundary of the GI system and reached a subsurface water source, while that of hybrid maple did not. London plane showed a slower response to water added in the tree pit soil, which can indicate the reduced dependence on GI soil water after plants have reached an alternative water source. Such reduction is not favored

because it defeats the purpose of having plants in GI systems. Designs using root barriers, appropriate plant species selection, etc. are recommended to avoid unwanted root spread. This study also found that GI design relying on upward water movements should be avoided because such design creates a narrow capillary zone on top of a saturated zone, which does not encourage transpiration.

KEY WORDS

leaf water potential; low impact development; stormwater control measure; tree trench; stomatal conductance; evapotranspiration; HYDRUS; simulated runoff test

INTRODUCTION

The use of green infrastructure (GI) to control non-point pollution associated with stormwater has been written into law by municipalities around the world (Botting and Bellette 1998, Roe and Mell 2013, US EPA 2019). Such laws protect surface water bodies in and adjacent to urban areas from contaminants transported by stormwater as well as those released during combined sewer overflow events (Tu and Smith 2018). By reducing the volume of stormwater entering combined sewer systems, GI lowers pollutant loading, runoff velocity, and peak flow rates (Ahiablame et al. 2012). Although GI systems need not be vegetated, plants and soils can contribute substantially to volume reduction, in particular by enhancing evapotranspiration (ET), interception, and infiltration (Buccola and Spolek 2011, Lucas and Greenway 2011, Yang and Li 2013, Tu and Traver 2019a). Evapotranspiration is arguably the most effective of these processes; studies using weighing lysimeters have found that 50% of precipitation can be removed by ET (Rejskova et al. 2012, DiGiovanni et al. 2013, Wadzuk, et al. 2013, Wadzuk et al. 2015, Zaremba et al. 2016, Hess et al. 2017). Moreover, vegetated GI systems provide additional ecosystem services such as improving air quality and cooling the local environment, thereby promoting human health (Wang et al. 2014).

Many stormwater control systems are deliberately overdesigned, i.e., built larger than required, to ensure that not only is the design goal achieved but that there is a margin for performance degradation through time (e.g., due to sedimentation). Overdesign is generally considered benign to stormwater control performance and is sometimes even favored (Vrban et al. 2018). However, there is mounting evidence that overdesign can have negative implications for plant water availability in systems designed to use stormwater as a primary water source for vegetation (Brown et al. 2015, Caplan et al. 2019). For plants that are unable to reach alternative water sources, overdesign may increase the frequency, intensity, and duration of plant water stress events, ultimately reducing transpiration rates and diminishing the associated benefits.

Any implications of overdesign for GI hydrology and plant water stress are likely to be moderated by plants' biological characteristics. For example, woody plants in overdesigned systems could be expected to experience water shortages more rapidly after storms compared to herbaceous species given their greater canopy-scale transpiration rates (Baldocchi et al. 2004). However, there may also be considerable differences among species within a given functional type. For example, variation in the size, architecture, or morphology of root systems are known to influence access to water and transpiration responses to varying soil moisture regimes (Reece and Riha 1991, Bouda et al. 2018).

A number of physiological measurements can provide insight into plant water relations, including water stress, though they have infrequently been used to evaluate GI systems. Transpiration (i.e., the efflux of water from a leaf or canopy) is the most widely used due to its importance in characterizing the water balance of many systems, but it is often measured in combination with evaporation (as ET). Moreover, transpiration is influenced by atmospheric conditions and therefore only loosely indicative of plant water stress. In contrast, stomatal conductance (g_s) is a metric that directly reflects the component of water release influenced by plants; g_s can be considered transpiration normalized to the evaporative demand of the atmosphere (specifically the vapor pressure gradient between the leaf and the air; Lambers et al. 1998). Values below approximately 200 mmol m^{-2} s^{-1} under well-lit conditions are often indicative of water stress in temperate species, though this is highly variable (). Perhaps the best measure of water stress is the potential of water in plant tissue, with measurements made on leaves when they are at their daily minimum near mid-day (Ψ_{md}) being the most commonly-used. Values below -1.5 MPa typically indicates a stressed state in species that are intolerant of drought or saline soils ().

A series of investigations was carried out to probe the dynamics of a tree trench suspected to have been overbuilt. Tree trenches are a type of GI in which one or more tree pits are embedded in a gravel-filled catchment. Stormwater is intended to enter the soil pits from below, such that these systems could be subject to hydrological limitation if overdesigned. This study had four objectives, each of which was addressed through a distinct investigation:

(1) Confirm that hydrological conditions in the tree trench indicate that it was overbuilt. This was done by determining the frequency that the stormwater level in the trench intercepted soil pits.
(2) Characterize the response of tree water relations to varying soil moisture conditions and determine how this response varies across species. This was done by evaluating how leaf water potential and stomatal conductance changed for two species in response to variation in soil moisture conditions throughout a growing season.
(3) Determine how soil moisture levels and tree water use respond to an extremely large storm event, i.e., the best case scenario with respect to stormwater delivery to tree pits' soil if the system is overdesigned. To achieve this, a simulated runoff test was conducted in the focal system simultaneous with repeated measurements of stomatal conductance.
(4) Evaluate how the system's design and soil type influence the soil moisture response to wetting by the infiltration bed. This was done using a 2D hydrologic model of a soil pit that was parameterized with empirical measurements of the soil's hydraulic properties and the time series of soil moisture during the simulated runoff test.

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MATERIALS AND METHODS

Site description

This study focused on a GI tree trench (212 m^2) located in northeast Philadelphia, USA, at 40.070° N, 75.175° W. The tree trench was constructed in 2013 and is composed of a gravel-filled infiltration bed installed beneath a sidewalk. Five trees and their associated soil pits (numbered T1 to T5) are embedded in the gravel bed (Fig. 1**Error! Reference source not found.**). The soil pits contain an engineered sandy soil (87.6% sand, 8.2% silt, 4.2% clay) surrounded with geotextile. The trees in T1, T3, and T5 are *Plantanus* × *acerifolia* 'Bloodgood' (London plane tree) while those in T2 and T4 are *Acer* × *freemanii* 'Armstrong' (Freeman's maple). The bottom of the infiltration bed is lined with a layer of sand 15 cm thick. Approximately 2,494 m^2 of road surface area drains to the trench at an 11.8:1 ratio of directly connected impervious area to treatment bed area. Two inlet structures (GI1 and GI2) collect runoff water from the street and a perforated distribution pipe delivers water collected by the inlet structures into the infiltration bed. The system was designed to retain runoff from a storm size of up to 47.5 mm without overflowing, and runoff that entered the bottom of the infiltration bed was intended to rise to the soil pits such that it would provide water to trees. Additional information about the site and tree trench system can be found in Tu and Traver (2018) and Caplan et al. (2019).

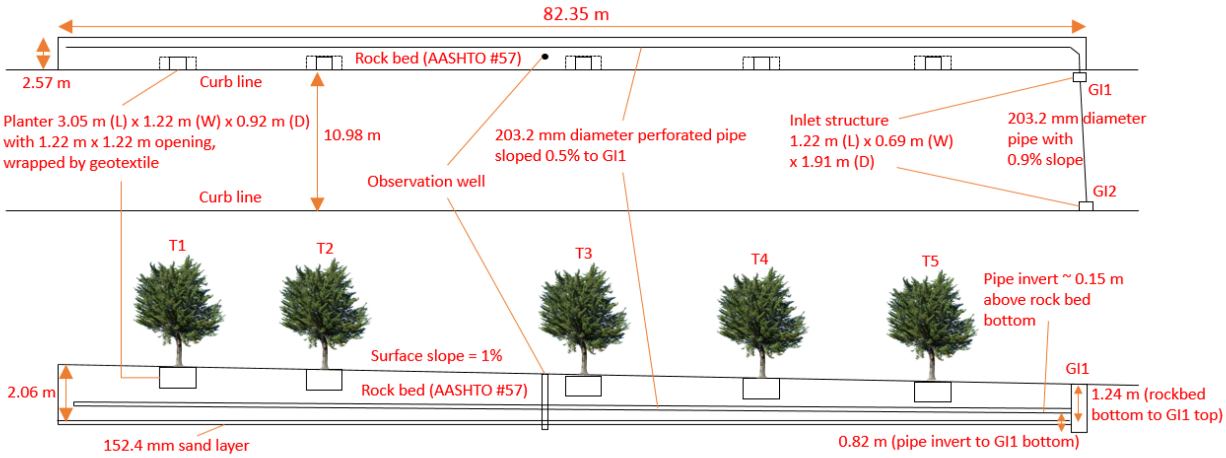

Figure 1. The green infrastructure system under investigation; plan view (top) and profile view (bottom). Reprinted from Tu and Traver (2018).

Hydrological characterization

A time series dataset of water depth in the trench was used to quantify the frequency that stormwater reached the bottom of each tree's soil pit. The dataset spanned March 2015 to April 2018, with data collected at 5 min intervals; 119 storms occurred during this period. A HOBO pressure transducer (Onset Computer Corporation 2019) recorded water depth in the infiltration bed; it was set into an observation well in the center of the trench (Fig. 1). Volumetric soil moisture content was measured at 5 min intervals in each soil pit using HydraProbe sensors (Stevens Water Monitoring Systems 2019) located at 10 cm and 35 cm depth with two additional sensors were installed at 60 cm in T2 and T4. The 60-cm sensor in T4 was the deepest by elevation. A weather station installed at the site monitored precipitation and other meteorological conditions; details are provided in Tu and Traver (2018).

Plant water stress

The response of tree water relations to varying soil moisture conditions was characterized from a dataset on mid-day leaf water potential (Ψ_{md}) and stomatal conductance (g_s) collected in 2015.

Procedures for data collection are described in detail elsewhere (Caplan et al. 2019) but briefly, Ψ_{md} and g_s were measured near mid-day (1100-1300 h) 1-2 times per week throughout the growing season (May to October) in each of the five trees. A leaf porometer (SC-1, Meter Environment, Logan, USA) was used to measure gs and a Scholander-type pressure chamber (PMS Instruments, Corvallis, USA) was used to measure Ψ_{md}. Records of the times when each physiological data point was collected were used to extract soil moisture data from an imputed time series representing levels at the 35 cm depth. Pearson correlation statistics were used to quantify the strength of the relationship between each water relations variable and soil moisture levels.

Simulated runoff test

A simulated runoff test (SRT) was performed on 1 August 2017 to investigate tree and trench dynamics under relatively extreme inflow conditions. Runoff water was provided by a street hydrant connected to a flow meter such that the release rate could be adjusted so the water depth would increase gradually and approximately linearly. Water was directed across the street surface so that it would flow towards the pair of inlets (Fig. 1) and enter the tree trench via the same pathway taken by runoff. The SRT began after a set of baseline measurements of tree performance was completed (see below) and proceeded for approximately 3.5 hours. Soil moisture, water depth, and associated hydrological data were collected throughout.

Trees' water use responses to the SRT were determined using measurements of g_s. Measurements spanned five time periods: one immediately prior to the SRT, three during the SRT, and one the morning after the SRT. In addition to the five trees in the focal tree trench, a London plane tree in an adjacent GSI system of the same design, but that did not experience the SRT, was also measured to provide a reference for diurnal changes in g_s. To account for variation in g_s within each tree's canopy, measurements were taken from at least three randomly selected leaves from both exterior and interior portions of the canopy (n = 6-14 measurements per tree per period).

A statistical analysis was performed to determine how g_s changed during the course of the SRT, if this differed from the tree in the adjacent trench, and if responses differed between species. A mixed-effects linear regression model was used; fixed effects included species identity, GI identity (i.e., SRT or non-SRT), canopy position (i.e., measurements taken in either the interior or exterior portion of the canopy), measurement period (a discrete variable with five levels), as well as all possible two-way interactions except GI identity × species (because only data of a single species were available for the non-SRT GI). A random effect for tree identity (discrete with 6 levels) was included to account for repeated measurements of individual trees. All hierarchically complete models were fit using maximum likelihood estimation via the *lme4* library in R (Bates et al. 2017), with binary variables coded ±0.5 and g_s centered and divided by two standard deviations (Gelman 2008). Model-averaged coefficients were then determined for all models with $\Delta AIC_c < 4$; coefficients for terms not present in a model were taken to be zero for the purpose of averaging. This process yielded robust coefficients (denoted β) proportional to each term's effect on g_s, as well as their unconditional standard errors and 95% confidence intervals (Grueber et al. 2011). The model term the first period defined the intercept of the model, such that terms for periods 2-5 represented deviations from it.

Hydrological modeling

A hydrological model was used to evaluate the response of soil moisture to wetting by stormwater from the infiltration bed. The model used (HYDRUS-2D) simulates water movement in variably saturated and unsaturated soil media by solving the Richards equation (PC-PROGRESS 2019); it was parameterized for a vertical plane through the T4 soil pit such that it intersected the position of a 60-cm soil moisture sensor (dashed line in Fig. 2). This location was selected because it allowed for direct comparison to the

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empirical soil moisture dataset. In the model, all boundaries below the elevation corresponding to the highest water level reached (during the SRT) were designated as having “variable head” conditions. The remaining side walls were designated as “seepage faces” because the pits were surrounded by gravel subject to atmospheric pressure (Ebrahimian and Noory 2014). No flow was assumed at the top boundary. Water retention parameters of the soil in the tree pits were derived empirically using a pair of intact cores. Pressure potentials and their corresponding water content values were measured with a HYPROP and WP4C (METER Environment 2019b). Parameters were determined by fitting the van Genuchten function to the combined datasets; parameter values from the two curves were averaged (Table 1). At the outset of model runs, soil moisture was set to match the value recorded by the soil moisture sensors (0.16 m^3 m^{-3}).

The geotextile was not depicted in the model. Given its permeability (0.274 cm s^{-1}) and thickness (0.15 cm), even if the flow velocity through the geotextile was equal to the soil’s saturated hydraulic conductivity tree pit (0.296 cm s^{-1}), the head loss generated by the geotextile would have been negligible (0.16 cm).

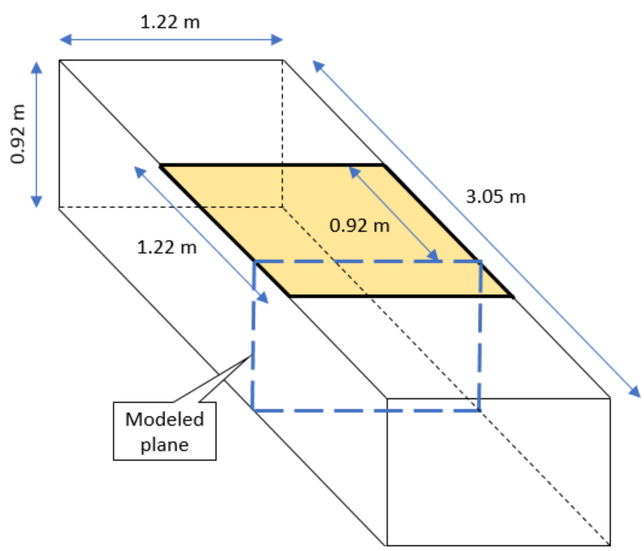

Figure 2. Location and orientation of the plane modeled in HYDRUS 2-D. The yellow square represents the opening in the sidewalk in which the tree is located and the blue dashed line represents the modeled plane.

Table 1. Parameters of the engineered soil's water retention curve as used in HYDRUS-2D

Parameter	Unit	Meaning	Value
Q_r	m^3 m^{-3}	Residual water content	0.029
Q_s	m^3 m^{-3}	Saturated water content	0.479
α	cm^{-1}	Air entry suction parameter	0.040
n	dimensionless	Pore size distribution parameter	1.344
K_s	cm min^{-1}	Saturated hydraulic conductivity	0.296

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RESULTS

Hydrological characterization

Of the 119 recorded storms between March 2015 and April 2018, 66 yielded enough water to be detectable in the infiltration bed. Excluding the SRT, none of these storms caused water to rise sufficiently high in the infiltration bed to reach the bottom of tree pits (Fig. 3). The maximum observed water depth was associated with a 69 mm storm and caused water to rise to 0.63 m. This was 0.03 m lower than the bottom of the T5 soil pit and 0.63 m lower than the bottom of the T1 soil pit.

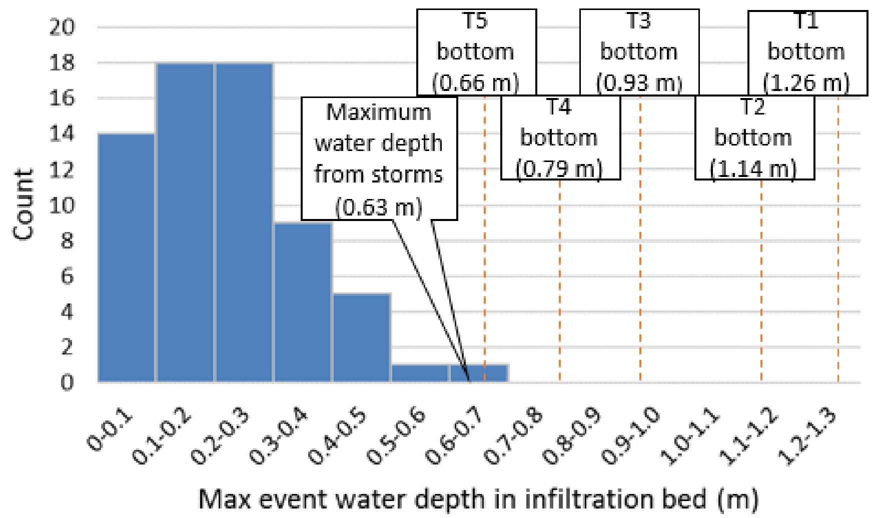

Figure 3. Distribution of maximum event water depth (natural storms only) in the tree trench's infiltration bed between March 2015 and April 2018.

Plant water stress

The transpiration behavior of woody plants in the overdesigned GI system was analyzed by comparing volumetric soil moisture (θ) and stomatal conductance (g_s) for London plane (*Platanus* x *acerifolia*, in T1, T3, and T5) and hybrid maple (*Acer* x *freemanji*, in T2 and T4) throughout the growing season of 2015 (Fig. 4). From Fig. 4, θ and g_s of London plane show little relationship with a Pearson pairwise correlation coefficient of -0.24, but such relationship for hybrid maple is stronger with a correlation coefficient of 0.34. The correlation coefficient for hybrid maple is even stronger (correlation coefficient = 0.54) for the lower θ region ($\theta < 0.2$).

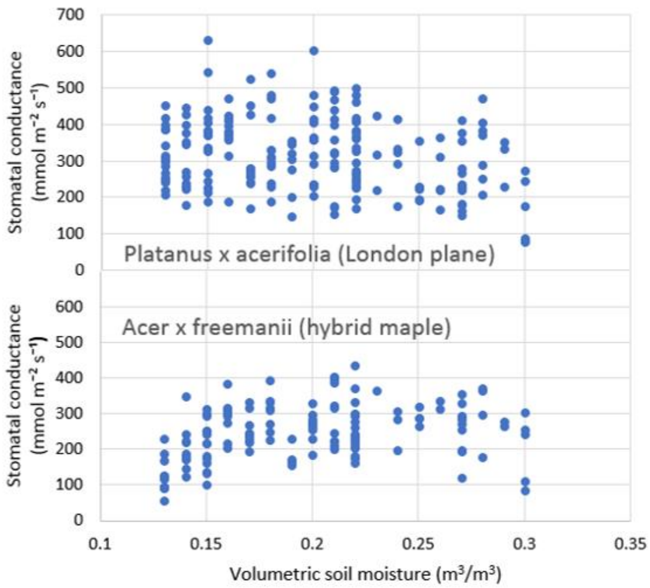

Figure 4. Relationship between soil moisture and stomatal conductance for both tree species.

Water stress due to dehydration (red shaded area in Fig. 5) was evaluated by leaf water potential (Ψ). Similar to the response of stomatal conductance, Ψ of London plane showed a weaker relationship (correlation coefficient = 0.50) with tree pit soil θ compared to that of hybrid maple (correlation coefficient = 0.66). It is also important to highlight that hybrid maple had experienced water stress for a substantial portion of the growing season of 2015, while London plane showed much fewer incidents of water stress.

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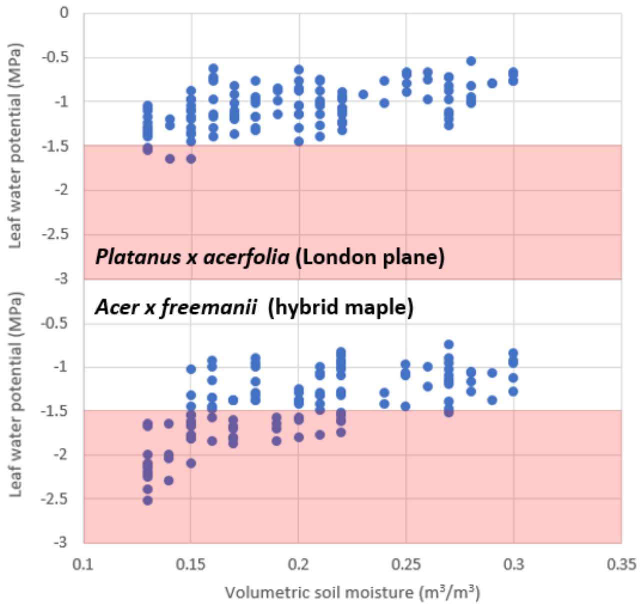

Figure 5. Comparison between soil moisture and stomatal conductance for both tree species. The red shaded area indicates the region (pressure magnitude > 1.5 MPa) where water stress is possible (Maarouf et al. 1999).

Simulated runoff test

Fig. 6 shows sub-hourly g_s, θ from the deepest soil moisture sensor (i.e., the 60-cm sensor in T4), and the water depth in the infiltration bed during the SRT and the following day. The SRT data were broken into five time periods, where Period 1 represents pre-SRT data, Periods 2-4 represent the beginning, middle, and end of the SRT, respectively, and Period 5 represents data in the following morning (after conclusion of the SRT). A storm with rainfall depth of 9.9 mm happened in the evening of August 1, 2017 (several hours after the conclusion of the SRT), which increased the soil moisture on August 2.

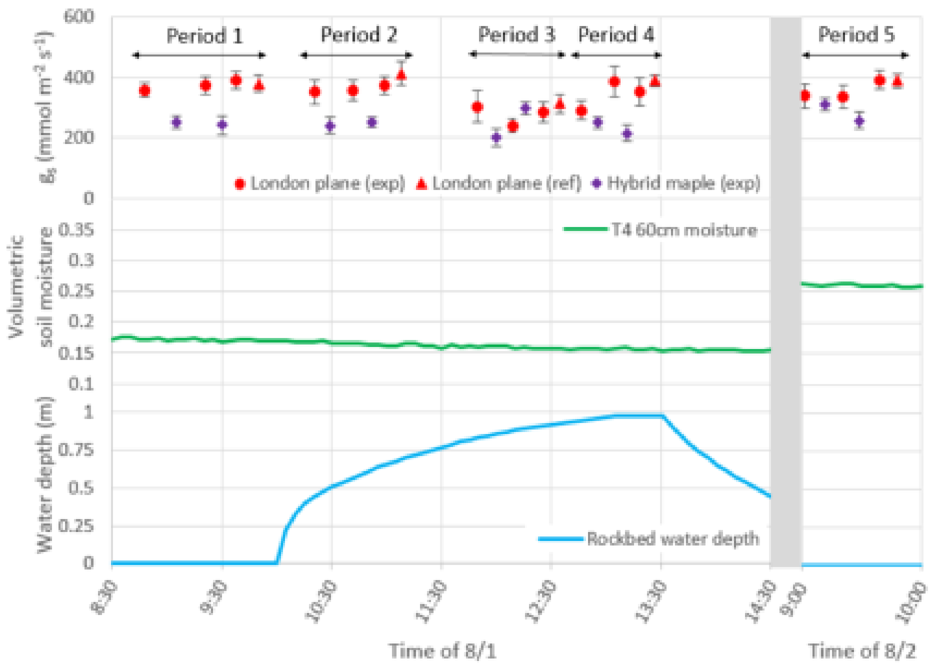

Figure 6. Data collected during the SRT of 8/1/2017 and the following day with the average and standard deviation of g_s for London plane with SRT (red circles), reference London plane without SRT (red triangles), and Hybrid maple with SRT (purple diamonds) were divided into five time periods. The volumetric soil moisture at 60 cm in T4 (green line) and rockbed water depth (blue line) are shown.

Table 2 provides results of the mixed-effects linear model analysis. Tree-level means of g_s remained between approximately 200 to 400 mmol m^{-2} s^{-1} during all measurement periods (Fig. 6); this was both the case for trees that did and did not experience the SRT. Statistical modeling showed that g_s in the non-SRT GI were marginally greater (β = -0.144 with 95% CI including zero). This difference regarding GI identity was likely because the non-SRT GI only contained London plane.

The greatest source of variation in g_s was species identity (London plane had substantially greater rates than the hybrid maple; β = 0.427). The second-strongest source of variation in g_s was canopy position. Leaves from the exterior portions of canopies also had greater g_s than those from canopy interiors (β = 0.375), as expected (Campbell et al. 1992).

The data presented no evidence that g_s differed among measurement periods except for Period 3. The value of g_s declined during Period 3 (11:30-12:30 on August 1) with β = -0.176 for the main effect; this effect was potentially greater for London plane (β = -0.251 for the interaction), though the coefficient's 95% CI included zero. The decline was likely a result of the trees restricting water loss in response to high evaporative demand during the middle part of the day. This phenomenon has been observed in other studies previously (e.g., Zhang et al. 2013). Even though Period 5 showed only a very minor overall increase in g_s (β = 0.098), hybrid maple showed greater influence on the increase of g_s (β = -0.135) in this period.

Even though Period 3 showed lower g_s, g_s returned to the same level in Period 4 (β = -0.038) while the weather conditions of Period 3 (11:30-12:30) and Period 4 (12:30-13:30) were similar. It can be hypothesized that some water did enter tree pits during the last hour of the SRT (period 4), which might have compensated for the water restriction experienced by the plant, so its g_s returned to the level of Period 1 and Period 2. Both species showed such recovery in Period 4 (β = 0.002).

Table 2. Statistical modeling results for a linear mixed-effects model of stomatal conductance with coefficients in bold showing model terms have higher influence with $|\beta| > 0.1$.

Model term	Coefficient (β)	SE	95% CI
Period 2	0.019	0.069	(-0.116, 0.155)
Period 3	**-0.176**	0.075	(-0.324, -0.029)
Period 4	-0.038	0.070	(-0.176, 0.099)
Period 5	0.098	0.070	(-0.040, 0.236)
Canopy position	**-0.375**	0.055	(-0.483, -0.268)
Species	**0.427**	0.100	(0.232, 0.622)
GI identity	**-0.144**	0.075	(-0.290, 0.003)
Period 2 x Species	0.022	0.119	(-0.211, 0.255)

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Period 3 x Species	**-0.251**	0.200	(-0.643, 0.140)
Period 4 x Species	0.002	0.119	(-0.232, 0.236)
Period 5 x Species	**-0.135**	0.146	(-0.421, 0.151)
Canopy position x Species	**-0.205**	0.110	(-0.420, 0.010)
Canopy position x GI identity	-0.016	0.068	(-0.149, 0.118)

Hydrological modeling

The observed soil moisture data in Fig. 6 showed no change of θ throughout the SRT, which was simulated in the HYDRUS-2D model. In Fig. 7, blue solid lines at the bottom and side represent the variable head boundary condition and the top of the blue line corresponds to the highest water level observed in the infiltration bed (Figure 6 at 13:30), and the dashed brown lines on the sides represent the seepage face boundary condition. From the simulation, the soil was close to saturation (θ = 0.45-0.479) below the elevation of the highest water level. Above the highest observed water level, the wetting front had a sharp vertical soil moisture gradient with θ dropping from near saturation to 0.16 in approximately 10 cm, so the wetting front did not quite reach the location of the 60-cm soil moisture sensor (white star in Fig. 7). This simulation results indicated that there was limited upward water movement and a thin capillary zone in the tree pit soil above the highest water level in the infiltration bed. Because the sandy GI soil had limited upward capillary lift, no change in soil moisture was measured above the background value of 0.16 $m^3\ m^{-3}$ at the 60-cm soil moisture sensor during the SRT (Figs 6 and 7).

Note that the SRT was performed four years after completion of the GI in 2013; therefore, clogging of the geotextile was possible (Veylon et al. 2016). Because no field data were available regarding the current state of the geotextile, this factor was not simulated, but the actual wetting front could be lower than modeled because hydraulic properties of the potentially degraded geotextile (i.e., providing more head loss).

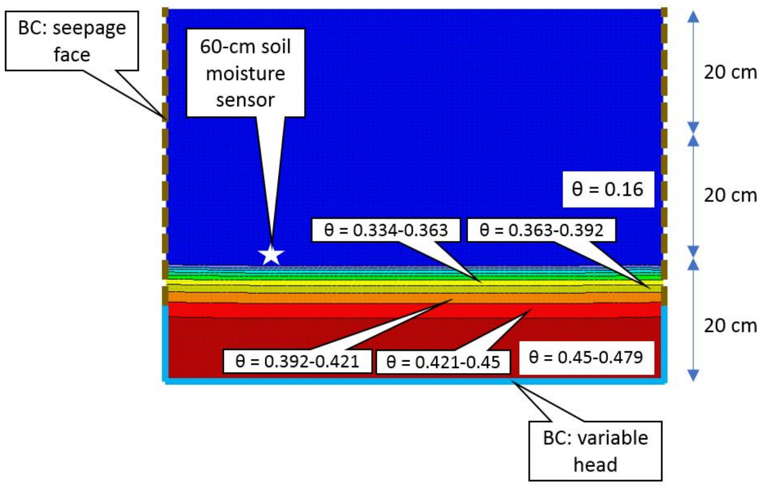

Figure 7. Simulation result at the end of SRT (13:30 in Fig. 6) before shutting down water supply and where the highest water level elevation was achieved

DISCUSSION

The SRT data showed stomatal conductance behaviors between the two tree species. For T3-T5, water started to enter the tree pit soil in Period 3 (as supported by both water elevation data of the infiltration bed and the HYDRUS modeling result), which was the period that both tree species started to show the restriction effect from high evaporation demands. As the analysis associated with Table 2 shows, London plane showed a more serious decline in g_s, implying that such additional water in tree pits had either smaller or slower influence on London plane. Similarly, tree pit soil received additional water between Period 4 and Period 5 because of the storm in the evening of August 1. Hybrid maple showed more increase in g_s in Period 5 compared to that of London plane. Both incidences could indicate that London plane has lower or slower response to moisture change of the tree pit soil.

One possible explanation to this observation, as Caplan et al. (2019) proposed, is the different water use strategies between isohydric and anisohydric plants. Isohydric plants tend to restrict g_s more strongly under drier conditions, while anisohydric plants maintain open stomata. The literature categorized London plane as an isohydric plant, which conforms with the observation in Period 3 of the SRT. However, it does not directly explain the prompt response of hybrid maple for water addition between Periods 4 and 5. Moreover, the literature did not provide a categorization for hybrid maple yet. Therefore, the explanation provided by Caplan et al. is plausible but still need more data and study to be confirmed.

An alternative hypothesis to explain this observation regarding the difference between the London plane and hybrid maple response is that London plane reached an alternative subsurface water source that decreased its dependence on changes of soil moisture in tree pit soil, while hybrid maple had not. Several indirect evidences can support such hypothesis, but more study is required. First, the long-term stomatal conductance (g_s) and leaf water potential (Ψ) data (Fig. 4) suggested that London plane has low dependence on water in the tree pit, while hybrid maple has a much higher dependency. Similarly, London plane showed few incidences of water stress (Fig. 5) for various θ (of tree pit soil) while hybrid maple showed frequent water stress in the same region of θ. Second, root-like tissues were frequently found protruding into the perforated orifices, as illustrated by the red oval in **Error! Reference source not found.**, which is a screenshot from a video clip recorded during subsurface cleaning in June 2016. One exemplary subsurface maintenance video record has been uploaded to the journal webpage associated with this paper. Caplan et al. (2019) also had the same finding and hypothesized that the roots have been able to penetrate beyond the infiltration bed and tap into alternative water source in the native soil. However, the roots of London plane and hybrid maple cannot be differentiated in Fig. 9 as the appearance of root tissue was distributed uniformly in the pipe (i.e., not concentrated at locations directly beneath trees). It might be caused by the fact that the spread of such root tissue is more prolific in the horizontal direction, particularly in a water-limited environment (Schenk and Jackson 2002).

Figure 8. Root penetration in the distribution pipe during subsurface cleaning in June 2016

A third reason to support London plane found an alternative water source is the above-ground canopy size. Fig. 10 showed that the canopy size of hybrid maple (T2 and T4) is smaller than that of London plane (T1, T3, and T5). Schenk and Jackson (2002) discovered that the rooting depth and lateral spread of woody plants can be related to above-ground volume in water-limited ecosystems. Such a relationship is particularly strong for woody plants between the lateral spread and above-ground volume. The larger canopy size of London plane implied that its root system is significantly larger than that of hybrid maple. Therefore, London plane is much more likely to reach alternative water sources beyond the soil pit.

Figure 9. Comparison of canopy size between hybrid maple (T2) and London plane (T3) on April 27, 2017 (sidewalk concrete panel serving as a reference, which is 1.22 m in width, photo by Min-cheng Tu)

Lastly, literature suggests that plants can adjust functionality of individual root parts according to soil conditions (Reece and Riha 1991, Lai and Katul 2000). Reece and Riha (1991) observed that trees tend to boost water uptake of the part of root that was not flooded in the first few days so that the whole tree does not show degradation of water uptake due to flooding (Else et al. 2009). Similarly, Lai and Katul (2000) found that the part of root that was not at the wilting point contributed primarily to water uptake compared to the part of root that was near the wilting point. Therefore, for the current study, it is reasonable to assume that the trees would choose to extract water from a more stable water source if there was more than one source.

In the end, it should be stressed that the tree pits were never in contact with water in the infiltration bed (except during the SRT) as the long-term water level data shows. Although Philadelphia has annual precipitation over 1000 mm and is not regularly a water-limited environment, each tree can only get water from the 1.22 m x 1.22 m surface openings due to hydrological disconnection with the infiltration bed. The hydrologic disconnection is due to an overdesigned system by volume and a media type that does not support capillary action. Thus, the trees were situated in a water-limited environment.

Both trees showed evidence that their root systems have expanded beyond the boundary of tree pits. Among these two species, the bigger trees (i.e., London plane) might even have accessed an alternative subsurface water source, which has become its primary water source because London plane showed low dependence on water in the tree pit and few incidences of water stress. Based on the reasoning above, it was hypothesized that under the water-limited condition, trees will rely on alternative subsurface water sources if they grow big enough to gain access to these alternative water sources. Moreover, such switch of water source might be semi-permanent, as London plane showed a slower response to water addition in the tree pits.

Such a water-limited environment was created by overdesign of the infiltration bed of the GI system, which was not necessary because the native soil has good infiltration capacity (Fig. 8). The infiltration bed draws down quickly (within 1-2 hours, Fig. 3), so overflow caused by statistically infrequent back-to-back storms (Wadzuk et al. 2017) is improbable. As a comparison to show the degree of overdesign, the City of Philadelphia Green Streets Design Manual (Philadelphia Water Department 2014) allows 72 hours for GI systems to fully drain.

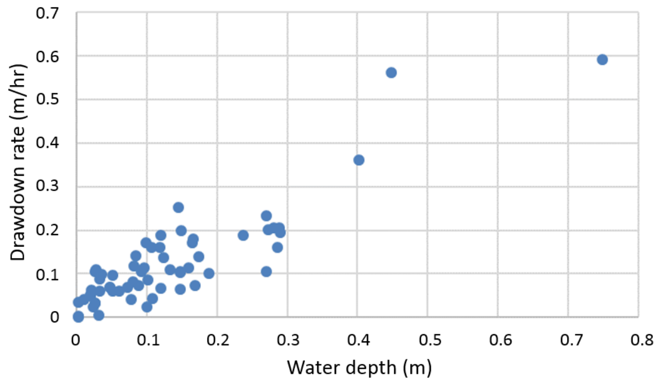

Figure 10. Comparison of maximum drawdown rate vs. water depth in the infiltration bed of all events including SRT.

Another finding and recommendation from these results is that designs should avoid relying primarily on the upward capillary force. In Period 3 and Period 4 of the SRT, water did enter the tree pit soil, but most water accumulated in the bottom of the tree pit soil. Only a very narrow capillary zone (10 cm) was observed (Fig. 7). It is known that plants can shut down transpiration by closing stomata when the soil is saturated (Else et al. 2009); therefore, water in the saturated part of the tree pit soil was not utilizable by plants. Future GI design should avoid the situation that water movement relies on the upward capillary force.

A second recommendation is that the limitations of SRTs should be better understood by researchers and practitioners. Implied by Fig. 4 in this study, soil moisture is not the only factor to control plant transpiration. Vapor Pressure Deficit (VPD) was found to be a more influential factor by Caplan et al. (2019). VPD represents the atmospheric demand for water, which can be calculated directly from temperature and relative humidity (Allen et al. 2005). Considering that evapotranspiration can take more than 50% of the water budget in the GI environment, this implies that the commonly used SRT might not be able to accurately simulate the performance of GI systems because the atmospheric condition (temperature and relative humidity) during storms cannot be replicated during SRT.

CONCLUSIONS

This study showed that when a GI system (in this case, the infiltration bed) is overdesigned, the ability of woody plants to transpire and be an agent in runoff storage capacity recharge is impacted. However, the woody plants did try to adapt to the environment by switching water demand from outside the GI system, as hypothesized by this study. Analyses on both the long-term and SRT data suggested that only London plane tapped into an alternative underground water source. Because London plane possibly tapped into an alternative water source, its transpiration response (in terms of g_s) showed slower/lower water stress response to water supply in the tree pit soil. Therefore, if water quantity reduction by vegetation in GI is the main goal, it is not advisable to allow root systems expanding beyond the boundary of GI systems because plants that found alternative water sources can decrease their water demand from the GI, thus defeating the original purpose to have plants in GI systems. Primarily, a vegetated GI system should be designed to support the selected plant community along with the stormwater management goals. Additionally, some possible practices that can be used in GI design are the adoption of root barriers to curb lateral root expansion, deeper soil depth to contain vertical root growth within the GI boundary, and the selection of smaller species so its root growth can be contained in the GI system. Schenk and Jackson (2002) found that some shrub species can have a positive relationship between root system sizes and rainfall depth, which means their root systems are smaller when water supply becomes scarce. Selection of these shrub species, instead of trees, might be a solution for overdesigned GI systems, but the issue of increased maintenance cost from higher mortality rate still exists (Varone et al. 2012).

The infiltration bed of the system under investigation was proven to be overdesigned by long-term water depth data in the infiltration bed. Under natural conditions, water in the infiltration bed never reached the tree pits; therefore, each plant receives water from only the sidewalk opening. Such prolonged dry conditions influence plant rooting. Schenk and Jackson (2002) showed that lower rainfall depth can influence trees to grow deeper root systems, albeit such a relationship is weak. Therefore, it is possible that the prolonged dry condition caused by the overdesign might have stimulated London plane to expand its root system beyond the boundary of the GI, but more research is needed to confirm such hypothesis.

Findings and hypotheses formed from this study can lead to numerous future research directions. For instance, a comparison study with London plane planted in a controlled environment such as the tree pit box designed by Asawa et al. (2017) can be performed. In such a controlled environment, plants cannot get additional water from other water sources; therefore, it is expected to see London plane have different responses in g_s. The result can be used to confirm or nullify the hypothesis of the current study that London plane has reached an alternative water source. Such experimental design can also provide a more robust temporal resolution of long-term g_s data to discern impact of environmental factors such as temperature, relative humidity, and solar radiation. Isotope study at the trees is another possible future research direction as the isotope signatures in surface water and in groundwater are different. Therefore, an isotope study can present solid evidence whether the trees are getting water from an alternative subsurface water source. Further, another future research direction is to identify how plants with different health conditions can influence their water uptake efficiency. This is important to affirm the conclusion of the current study. In the current study, the effect of restricting plant roots in the GI system was overlooked and the focus was the source of water uptake. For trees with roots limited in the GI system, water stress might cause the trees to grow less healthy. Compared to a healthy tree that has tapped into a subsurface water source and only a minor part of water uptake is from the GI system, the unhealthy tree can take less water from the GI system because of its health condition. Due to the limitation of available data, this is something that cannot be investigated in the current study but is worth investigating in future research..

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