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Tree Species Suitability to Bioswales and Impact on the Urban Water Budget

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Abstract

Water movement between soil and the atmosphere is restricted by hardscapes in the urban environment. Some green infrastructure is intended to increase infiltration and storage of water, thus decreasing runoff and discharge of urban stormwater. Bioswales are a critical component of a water-sensitive urban design (or a low-impact urban design), and incorporation of trees into these green infrastructural components is believed to be a novel way to return stored water to the atmosphere via transpiration. This research was conducted in The Morton Arboretum's main parking lot, which is one of the first and largest green infrastructure installations in the midwestern United States. The parking lot is constructed of permeable pavers and tree bioswales. Trees in bioswales were evaluated for growth and condition and for their effects on water cycling via transpiration. Our data indicate that trees in bioswales accounted for 46 to 72% of total water outputs via transpiration, thereby reducing runoff and discharge from the parking lot. By evaluating the stomatal conductance, diameter growth, and condition of a variety of tree species in these bioswales, we found that not all species are equally suited for bioswales and that not all are equivalent in their transpiration and growth rates, thereby contributing differentially to the functional capacity of bioswales. We conclude that species with high stomatal conductance and large mature form are likely to contribute best to bioswale function.

Stormwater runoff occurs when excess stormwater flows over the ground surface rather than infiltrating into the soil. Research has shown that stormwater runoff negatively affects downstream water bodies, resulting in severe channel erosion (Paul and Meyer, 2001), flooding (USEPA, 2005), unsafe drinking water (Schoonover et al., 2005), decreased groundwater recharge (Shuster et al., 2007), and reduced stream baseflow during dry periods (Schoonover et al., 2006). The pollutants in runoff that result in aquatic habitat degradation (Coleman II et al., 2011) can include sediments, nutrients, metals, synthetic organics, pathogens, and hydrocarbons (Greenstein et al., 2004; Mazer et al., 2001). Pending improved stormwater management, it is reasonable to believe that the issues arising from runoff will be exacerbated by the increased area of impermeable surfaces (e.g., roof tops and pavements) that result from continued urbanization (Valtanen et al., 2014). To limit the consequences of stormwater runoff, principles and practices have evolved globally and are known under various names, such as sustainable urban drainage systems, low-impact development, water-sensitive urban design, and best management practices (Fletcher et al., 2014).

A specific practice adopted to minimize the impact of stormwater runoff involves the use of biofilters, also called biofiltration or bioretention systems (Read et al., 2008) or biofiltration swales or bioswales (Mazer et al., 2001). Biofilters are vegetated channels designed to reduce runoff volumes and/or to remove dissolved pollutants and particulate matter from stormwater runoff (Read et al., 2008). Their flexibility in size and configuration allows them to be located in an array of urban landscapes (Bratieres et al., 2008).

A key component of biofilter design is vegetation, which absorbs pollutants and stormwater (Hatt et al., 2009). The choice of vegetation varies but can include tussocks, forbs, shrubs, and trees (Read et al., 2008). The size of vegetation is an important factor in determining the function of biofilters (Bratieres et al., 2008; Read et al., 2008). Trees may be best suited to improving the performance of biofilters because their large above- and

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Abbreviations: DBH, diameter at breast height; g_s, stomatal conductance; HSD, honest significant difference.

below-ground biomass maximizes their potential effect on stormwater dynamics, relative to smaller-statured vegetation forms. The utility of trees in biofilters extends beyond absorption of water and pollutants by roots. By producing root channels through compacted subsoils, trees can limit runoff by increasing water infiltration rates (Bartens et al., 2008). Trees also limit runoff by intercepting rainfall with their leaves, where it remains until it is evaporated or moved into the soil via trunk flow (Livesley et al., 2014; Xiao et al., 1998; Xiao and McPherson, 2011). Knowing that vegetation morphology, physiology, and even mycorrhizal associations can alter biofilter performance (Bratieres et al., 2008; Read et al., 2008), it is clear that species selection is important.

The literature on species choice for biofilter performance optimization remains scarce, and it is unclear which species, or even which vegetative forms, are most suitable for biofilters. Whether plants can thrive in the bioswale environment must be considered; species will likely respond differently to intermittent wetting and drying and to elevated levels of macronutrients, sediment, heavy metals, and hydrocarbons (Read et al., 2008).

Previous literature on vegetation response to the bioswale environment or stormwater application is inconclusive. Mazer et al. (2001) reported that grass biomass in bioswales decreased due to prolonged inundation, although this effect was muted in low light conditions. Read et al. (2008) reported no change in chlorophyll fluorescence due to stormwater application for 20 different species, including five tree species. Denman et al. (2006) reported increased growth for trees receiving a stormwater treatment, and Xiao and McPherson (2011) reported improved growth of leaves and new branches in a structural soil bioswale.

There is evidently a need to better understand species response to bioswale environments, particularly in field conditions (Bratieres et al., 2008). Furthermore, there is very little research on how trees affect the urban water budget (Bartens et al., 2008). Field data quantifying tree transpiration would be very valuable for improving our understanding of the importance of trees in parking lot biofiltration swales.

To this end, trees in The Morton Arboretum's parking lot were studied in three experiments to understand their performance in bioswales and their impacts on the urban water budget. Here we characterize soil moisture, electrical conductivity, pH, and soil organic matter in bioswales and determine how different tree species respond to these conditions. The latter question is answered by measuring stomatal conductance (g_s), leaf color, growth, and vitality metrics for trees in the bioswale. Stomatal conductance was studied over one growing season to quantify transpiration of the bioswale trees and to better understand the effects of trees on the water budget. Finally, we monitored water inputs and outputs over 3 yr to determine the efficacy of the parking lot system to direct and retain stormwater.

Materials and Methods

Study Site

This research was conducted at The Morton Arboretum, which is a 700+ ha outdoor museum of woody plants located in DuPage County, Illinois, approximately 30 km west of Chicago. In the late 1990s, The Morton Arboretum underwent a large-scale redevelopment of their visitor center, main entrance, and parking lot. The redevelopment included the construction of a "green" parking lot, incorporating numerous best management practices to capture and filter rainwater before entering adjacent Meadow Lake and East Branch of the DuPage River (Supplemental Fig. S1). The 2-ha green parking lot includes bioswale medians and permeable pavement and has 500 car parking spots. Permeable pavers cover 1.9 ha of the parking lot, with 1.6 ha in Ecoloc permeable interlocking concrete pavers (Unilock) and 0.3 ha in UNI-Anchorlock solid interlocking pavers (Unilock). Bioswales in the green parking lot contain single- and multi-stemmed deciduous and evergreen trees, shrubs, and herbaceous plants. The bioswales are 3 m wide and graded at a 3:1 slope from the edge of curb to the swale bottom (30 cm) (Supplemental Fig. S2). The bioswales receive water from the parking lot in 1-m gaps spaced 9 m apart. Planting soil (46 cm) in the bioswales was a constructed sandy loam (60% sand and 10% clay) with 5% coarse organic matter and pH 5.5 to 7.5 at installation. Perforated high-density polyethylene storm sewers (0.76 m in diameter) are under the planting soil within the CA1 sub-base to handle a 10-yr storm event. The storm sewers are interconnected with catch basins for sediment and pitched (0.5%) toward a water-level control structure, which drains to Meadow Lake. The control structure can restrict flow out of the storm sewer system to allow for additional time to infiltrate into the sub-base. Alternatively, the structure can be opened to allow for rapid flow when the sub-base is not draining quickly enough to maintain the pavement integrity.

Experiment I: Soil Characterization and Tree Physiological Response

Experiment I compared tree leaf attributes and soil properties in bioswales with trees in the surrounding nonbioswale areas (hereafter referred to as the "null" areas). For this experiment, 42 trees in the parking lot (Supplemental Table S1) were paired with like trees in null areas of The Morton Arboretum. Pairings were based on like accession numbers, allowing a comparison of two trees in dissimilar growing conditions (bioswale and null) of like species, age, planting age, and source of the plant material (Supplemental Table S1). The null trees were located in the surrounding non–parking lot landscaped areas of The Morton Arboretum and were similar in light availability, distance to hard space, and management to the parking lot trees except that they were not in bioswales. Most of the null trees were located in the Children's Garden, near the Visitor Center, and within the landscaped areas surrounding the Research Building. The experimental design included seven species (*Acer campestre* L., *Acer miyabei* 'Morton' *Acer* x *freemanii* 'Jeffersred', *Carpinus caroliniana* 'Walter', *Cercis canadensis* L. *Quercus macrocarpa*, and *Syringa pekinsis* 'Morton'), two growing environments (independent variable) (bioswale vs. null), and three replicates of each species and environment for a total of 42 trees.

The dependent variables tested in this experiment included tree and soil attributes, which were monitored from mid-June to late August 2014. Stomatal conductance (mmol m^{-2} s^{-1}) and soil moisture (%) were measured weekly. On each sample date, three leaves (one in the shade and two in sunlight) of each tree were assessed with a leaf porometer (SC-1 Leaf Porometer, Decagon Devices). Measurements of g_s were made between 10:00 and

14:00 h on each day to capture the daily maximum g_s rate. To verify that g_s peaked between these hours, measurements were made on 22 July 2014 at 0800, 1000, 1200, and 1400 h. Across all species, g_s increased from 0800 h to a peak between 1000 and 1200 h and decreased to a low at 1400 to 1600 h (data not shown). Buriable time domain reflectometry probes (6050X1 Trase System, Soil Moisture Equipment Corp.) were installed vertically from the surface to 20 cm depth half way between the trunk and the drip line, approximately 2 to 3 m from the trunk in the southern quadrant of each tree. Leaf greenness was measured on 11 and 30 July 2014 by assessing 10 random leaves on for each tree with a SPAD 502 Plus Chlorophyll Meter (Spectrum Technologies). Soils were collected from each of the 42 trees on 15 July 2014. At each tree, a five-core composite from the 0- to 20-cm depth was collected using a 2.5-cm-diameter core sampler (Oakfield Apparatus). Soils were analyzed for gravimetric soil moisture to correct volumetric soil moisture readings with TDR probes (Topp and Ferré, 2002). Soils were also analyzed for pH in a 1:1 solution (soil:deionized water) (Thomas, 1996), electrical conductivity in a 1:4 solution (soil:deionized water) (Rhoades, 1996), and loss-on-ignition soil organic matter (Nelson and Sommers, 1996).

Experiment II: Tree Growth and Condition

Experiment II examined tree growth and qualitative indices of tree condition in bioswale vs. null environments. For this experiment, all single-stemmed trees in the parking lot were assessed for tree growth and condition. In total, 63 trees spanning 11 genera and 16 species were included (Supplemental Table S2). Sixty-three trees were identified in null environments within The Morton Arboretum collection and landscape area in close proximity to the parking lot. Based on accession numbers, comparison trees were selected so that bioswale and nonswale trees were of like species, age, planting age, and source of material. For example, in 2003 two *Quercus rubra* 'Crystal' were planted in the parking lot. In that same year and from the same shipment, two other *Q. rubra* 'Crystal' were planted in the Children's Garden. On 4 Sept. 2014, the 126 trees in this experiment were assessed for the following dependent variables.

Diameter growth rate (cm yr^{-1}) was computed for each tree by measuring the diameter at breast height (DBH) (1.4 m) and dividing by the number of years that tree had been in the landscape. The commonly reported "relative growth rate" could not be calculated because the DBH of each tree at planting was not known. Nevertheless, the DBHs for each pairing were likely to have been very similar at planting because paired trees were the same age and arrived in the same shipment from the nursery.

A tree condition index was derived from four qualitative assessments (vitality, opacity, quality, and twig growth) of tree condition (Bond, 2012). Each of the four metrics is assigned a score from 0 to 5, where higher scores are given for better tree condition. Vitality is the percentage of the crown that is free from recent mortality (no live crown = 0, 1–20% = 1, 21–40% = 2, 41–60% = 3, 61–80% = 4, and >80% = 5). Opacity is the percentage of light visibility blocked by branches, foliage, and reproductive structures of the actual live crown (no live crown = 0, 1–20% = 1, 21–40% = 2, 41–60% = 3, 61–80% = 4, and >80% = 5). Quality measures the percentage of the crown that is free from necrotic, chlorotic, or undersized foliage (no live crown = 0, 1–20% = 1, 21–40% = 2, 41–60% = 3, 61–80% = 4, and >80% = 5). Twig growth is the 3-yr average terminal shoot extension on three random branches that were not recently pruned or damaged (no live crown = 0, <5 cm = 1, 5–10 cm = 2, 10–15 cm = 3, 15–20 cm = 4, and >20 cm = 5). Finally, the tree condition index (0–1) is computed by summing the ratings of vitality, opacity, quality, and twig growth and dividing that score by 20. To ensure consistency, the same individual performed all the qualitative assessments.

Experiment III: Water Budget

Water inputs (precipitation), outputs (discharge), and runoff were measured continuously in The Morton Arboretum parking lot from April to October each year from 2012 to 2014. Precipitation was recorded every 5 min on-site with a tipping bucket rain gauge and data logger (RG600 and GL500-2-1, Global Water). Runoff from permeable surfaces within the green parking lot was measured at three inlets using water level loggers (WL16U, Global Water). Runoff from three adjacent paired asphalt inlets was also measured using similar water level loggers. Runoff measurements were made every 15 min. All runoff from the parking lot plus water that enters the parking lot bioswales that is not taken up by vegetation, stored in soil, leached below the sub-base, or lost as evaporation drains to sewer drains under the bioswales. The sewer drains are sloped at 0.5% and channel to one outlet (0.76 m in diameter) with a water level control structure to discharge to Meadow Lake. A water level logger (WL16U, Global Water) was installed at this outlet to measure the discharge every 15 min from the parking lot to Meadow Lake. Precipitation, runoff, and total discharge were summed for daily and monthly flow rates.

A monthly water balance was computed for the parking lot with the water flow, g_s, and soil moisture measurements from Experiment I. Water inputs included the measured precipitation and irrigation. Irrigation was estimated based on 508 sprinkler heads running 12 cycles per week at 45 min cycle^{-1} at 1 L min^{-1}. Water outputs from the parking lot included transpiration from trees, storage in soil, discharge to Meadow Lake, and an unmeasured component. The unmeasured flow contains the water lost in evaporation, transpiration by vegetation other than trees, runoff lost from the site, leaching not collected by the sewers, and water storage in vegetation.

Tree transpiration was modeled, with mean monthly g_s values computed for each species in Experiment I. Data from the most closely associated species based on similarities in physiological traits were used for species in which g_s was not specifically measured. Diurnal patterns in transpiration were determined by measurements of g_s on 22 July 2014 at 0800, 1000, 1200, and 1400 h. Daily g_s was predicted from the mean monthly g_s values for each species by applying the integration factor of 0.18. Using our diurnal g_s data, we found that the integrated mean g_s value was 0.18 of the maximum (or measured) daily g_s value. For example, 209.2 mmol m^{-2} s^{-1} was the maximum g_s measured for *A. miyabei* in June, and this value was multiplied by 0.18 to adjust for decreases in g_s earlier and later in the day and cessation at night. Leaf area (m^2) for each tree was calculated from DBH using equations and shading factors by unique species listed in Nowak (1996), and the effective leaf area was computed by dividing this number by two.

Soil storage was modeled from measured volumetric soil water contents in Experiment I using a bioswale area of 3956 m^2 and a depth of 0.46 m. The maximum volume of water that could be held in the bioswale soil was 45.2 Mg, which is based on 0.25 volumetric moisture content after freely drained water is removed. No soil storage was included for water that might be retained in the CA1 sub-base below the bioswale planting soil. Discharge from the parking lot was measured directly from the water level loggers at the outlet to Meadow Lake. The unmeasured flow was computed by Inputs (precipitation + irrigation) − Outputs (tree transpiration + soil storage + discharge).

Statistical Analysis

Statistical analyses were conducted using SAS JMP 11.0 software (SAS Institute Inc.). The assumptions of constant variance and independence among residuals were checked with standard diagnostic plots. Normality in the residuals was checked using the Shapiro–Wilk W test. Responses were analyzed for effects of location (bioswale vs. null) using ANOVA. Mean separations were conducted using Tukey–Kramer honest significant difference (HSD) test. Linear regression analyses were conducted to examine correlations among soil and tree responses. All statistically significant differences are reported at the $P < 0.05$ level.

Results

Experiment I: Soil Characterization and Tree Physiological Response

Soil moisture and organic matter were significantly greater in the nonswale environments (Table 1; Fig. 1), whereas pH was significantly greater in the bioswale, and electrical conductivity did not differ between the two locations. Although soil properties differed when comparing the bioswale and null planting locations, most soil properties were not significantly correlated ($P > 0.05$) with g_s or leaf color. One exception was electrical conductivity, which was negatively correlated with g_s. However, electrical conductivity explained only a modest amount of the variation in g_s ($R^2 = 0.207$; $P = 0.0028$).

The overall mean g_s for trees planted in bioswales did not differ significantly from trees planted outside the bioswales (Table 1). However, an interaction effect shows that g_s was significantly greater for trees in bioswales for two of the eight measurement dates (28 Aug. 2014 and 5 Sept. 2014), both at the end of the growing season (Fig. 2). Stomatal conductance differed significantly among species, although a significant species by date interaction was also detected. The species effect on g_s was significant on all dates except 28 Aug. 2014. Tukey–Kramer HSD mean g_s for *Q. macrocarpa* was significantly greater than all other

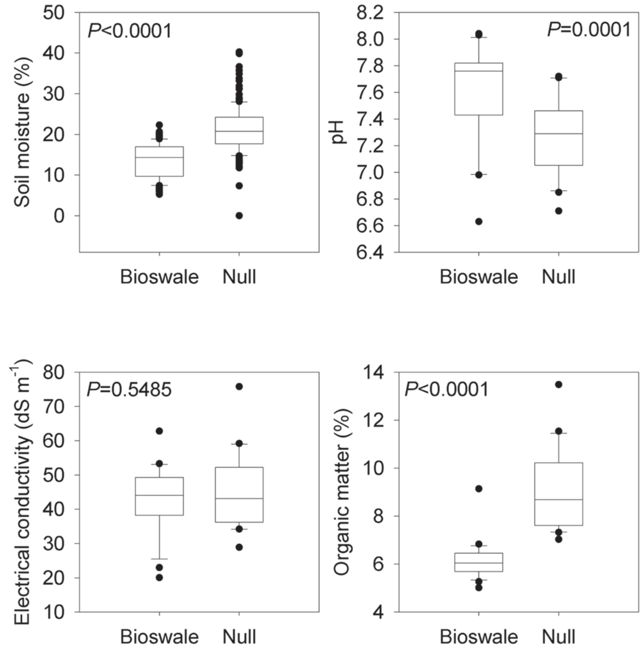

Fig. 1. Soil moisture, pH, electrical conductivity, and organic matter (0–25 cm) in bioswales of The Morton Arboretum parking lot and adjacent nonbioswale (null) locations. * $P < 0.05$.

species, regardless of whether trees were inside or outside the bioswale (Fig. 3). Mean g_s was lowest for *C. caroliniana* and was significantly lower than *A. campestre*, *A. miyabei*, *Q. macrocarpa*, and *Syringa pekinensis* Rupr. Within-species one-way ANOVA using location as the effect showed that *C. caroliniana* exhibited greater g_s in the bioswales, whereas the opposite was true for *C. canadensis*. The mean g_s for all five other species did not differ from the bioswale to the null location. Leaf color did not differ among trees planted inside or outside the bioswales. As expected, significant differences in leaf color were observed due to species.

Experiment II: Tree Growth and Condition

Overall mean diameter growth rate was significantly ($P = 0.0095$) greater for trees planted in bioswales. Some genera displayed greater diameter growth rates in bioswales compared with their growth in null environments, specifically *Cercis*, *Fraxinus*, *Gymnocladus*, and *Ulmus* (Fig. 4). Across both bioswale and null locations, *Ulmus* had the greatest diameter growth rate of all genera. Following *Ulmus*, diameter growth rate was greater for *Acer* compared with *Fraxinus*, *Celtis*, and *Quercus*. Despite the relatively high tree condition index of *Gymnocladus* in bioswales, the overall mean tree condition index (i.e., the sum of scores for vitality, quality, opacity, and twig growth) did not differ among trees planted in bioswale or null planting locations (data not shown). In contrast, overall mean tree condition index

Table 1. Prob > F values for ANOVA effect tests of species, location, date, and interactions for tree and soil response data.

Response	Species	Location	Date	Species location	Species × date	Location × date	Species × location × date
Stomatal conductance, mmol m^{-2} s^{-1}	<0.0001	0.1465	0.0086	0.5142	<0.0001	0.0049	0.2154
Leaf color (SPAD units)	<0.0001	0.0944	0.2800	0.5314	0.7497	0.7118	0.8396
Soil moisture, %	0.2652	<0.0001	<0.0001	0.7473	0.7845	0.0002	0.7402
pH	0.0037	0.0001	–	0.0599	–	–	–
Electrical conductivity, dS m^{-1}	0.6105	0.5485	–	0.7690	–	–	–
Organic matter, %	0.4631	<0.0001	–	0.4406	–	–	–

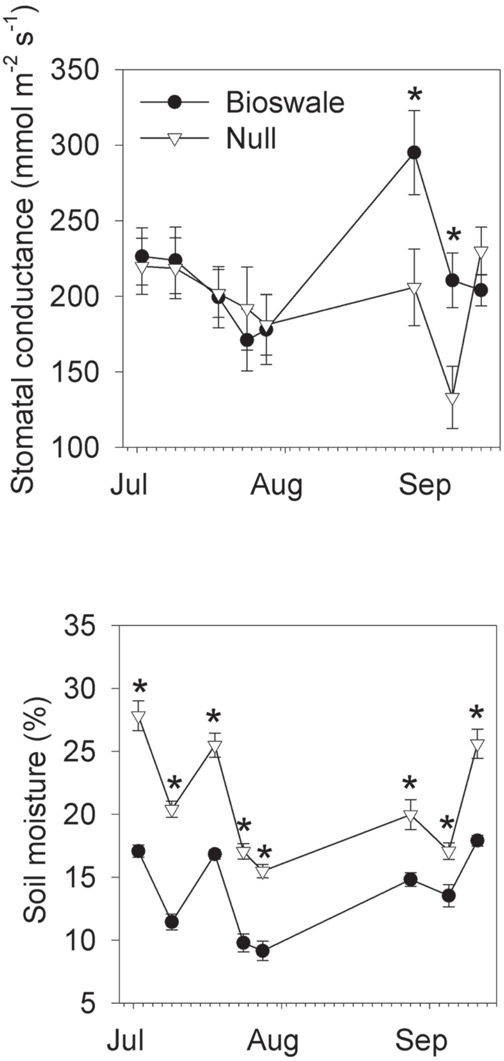

Fig. 2. Stomatal conductance and soil moisture in bioswales of The Morton Arboretum parking lot and adjacent nonbioswale (null) locations during July through September 2014. * $P < 0.05$.

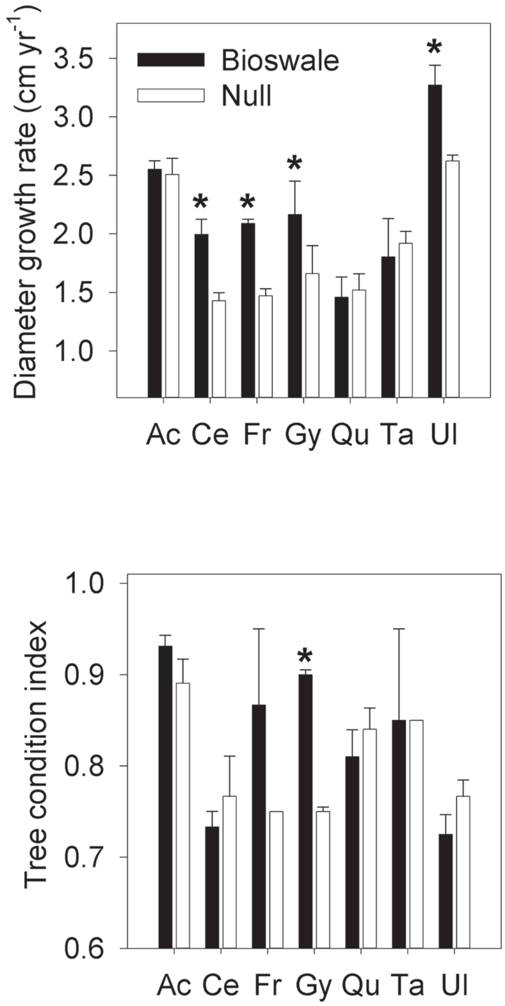

Fig. 4. Diameter growth rate and tree condition index by genera of trees in bioswales of The Morton Arboretum parking lot and adjacent nonbioswale (null) locations on 4 Sept. 2014. * $P < 0.05$. Ac, *Acer*; Ce, *Cercis*; Fr, *Fraxinus*; Gy, *Gymnocladus*; Qu, *Quercus*; Ta, *Taxodium*; Ul, *Ulmus*.

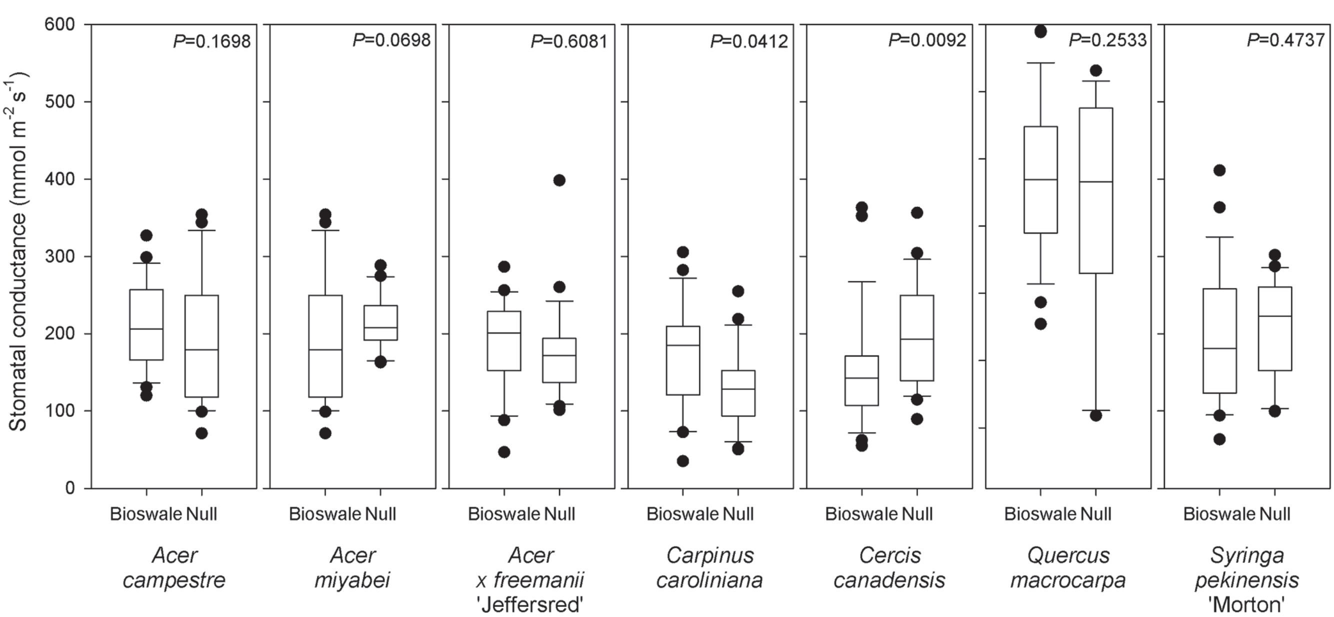

Fig. 3. Stomatal conductance by species in bioswales of The Morton Arboretum parking lot and adjacent nonbioswale (null) locations during July through September 2014.

did differ significantly across genera, with a Tukey–Kramer HSD test identifying *Acer* as having a higher tree condition index than *Ulmus*. No other genera differences existed.

Experiment III: Water Budget

During the growing seasons 2012 to 2014 (May–Oct.), monthly precipitation ranged from 4.8 to 20 cm (Fig. 5). Growing season precipitation in 2012 was relatively low (49.2 cm) compared with 2013 (66.5 cm) and 2014 (72.0 cm). The 20-yr mean total precipitation for May through October for Lisle, IL is 57.9 cm (NOAA, 2014). During the 2012, 2013, and 2014 growing seasons, monthly discharge from the parking lot ranged from 0 to 2.1 cm. No discharge was measured for 9 of the 18 mo. The peak discharge (2.1 cm) was measured from 21 to 27 Aug. 2014. Just before that peak discharge, the parking lot received a large pulse of rain (11.9 cm) over three consecutive days (21–23 Aug. 2014). This 3-d precipitation event exceeded the total precipitation in August of 2012 and 2013. Monthly runoff was significantly greater on asphalt surfaces compared with permeable surfaces for 13 of 18 mo (Fig. 5). For the 5 mo in which no differences were observed between asphalt and permeable surface runoff, variation in runoff for permeable surfaces tended to be higher, potentially masking any differences.

A detailed examination of the parking lot water budget was conducted for the period of June through September 2014 (Fig. 6). The total input of water to the parking lot during this time was 15,793 Mg, with 10,909 Mg in precipitation and 4884 Mg in irrigation. Precipitation exceeded irrigation in all months, and the highest water input was for the month of August 2014 (3736 Mg). Water outputs for the parking lot included transpiration, soil storage, discharge, and unmeasured. Tree transpiration represents the major water output from the parking lot, ranging from 2009 to 3028 Mg of water per month, or a total of 9194 Mg for June to September 2014. Tree transpiration accounted for 46 to 72% of the water inputs in precipitation and irrigation. Soil storage and discharge were minimal, accounting for 4.5 to 10% and 0.02 to 1.7% of water inputs, respectively. The total unmeasured stock accounted for 18 to 49% of water inputs. The unmeasured stock was likely a combination of shrub and herbaceous transpiration leaching out of the soil, uncaptured runoff from the site, plant storage, and evaporation.

Discussion

The urban water cycle differs from natural systems in that runoff is often increased due to hard surfaces preventing infiltration (Scheyer and Hipple, 2005). Green infrastructure is intended to increase infiltration and storage, thus decreasing discharge and runoff of urban stormwater (Tzoulas et al., 2007). Bioswales and permeable surfaces in The Morton Arboretum parking lot appear to be very effective at decreasing discharge and runoff. Over the course of the monitoring period, discharge from the parking lot ranged from 0.02 to 1.7% (mean, 0.5%) of total water inputs. On average, monthly runoff on asphalt exceeded permeable surfaces by 69.9% (15.6–99.3%).

One of the objectives of this research was to better understand the specific role of trees in the bioswale water balance. After all, trees are often included in green infrastructure and are proposed to have many roles in stormwater management, including direct interception, transfer via stemflow, increased infiltration, and transpiration (Breen et al., 2004). However, very little

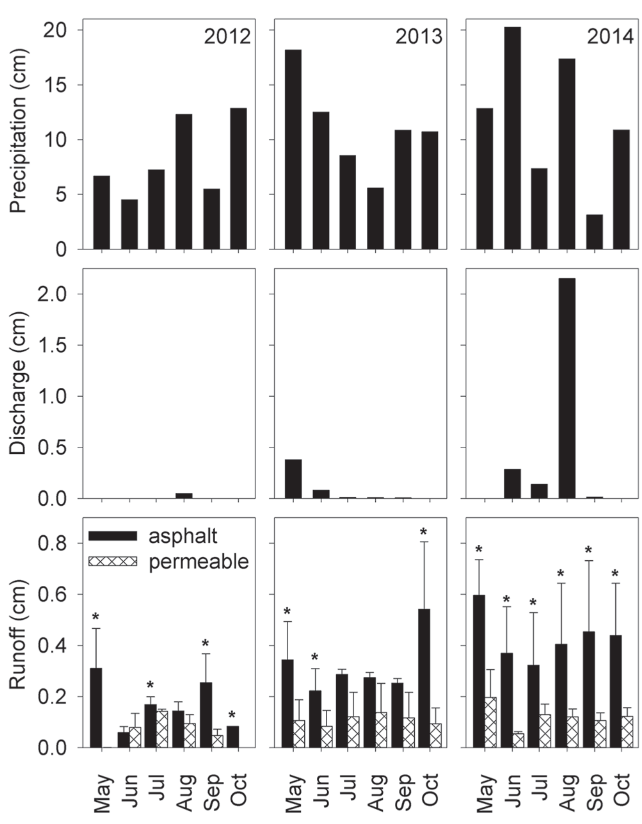

Fig. 5. Monthly total precipitation, discharge, and runoff into and out of The Morton Arboretum parking lot during May through October in 2012, 2013, and 2014. * $P < 0.05$.

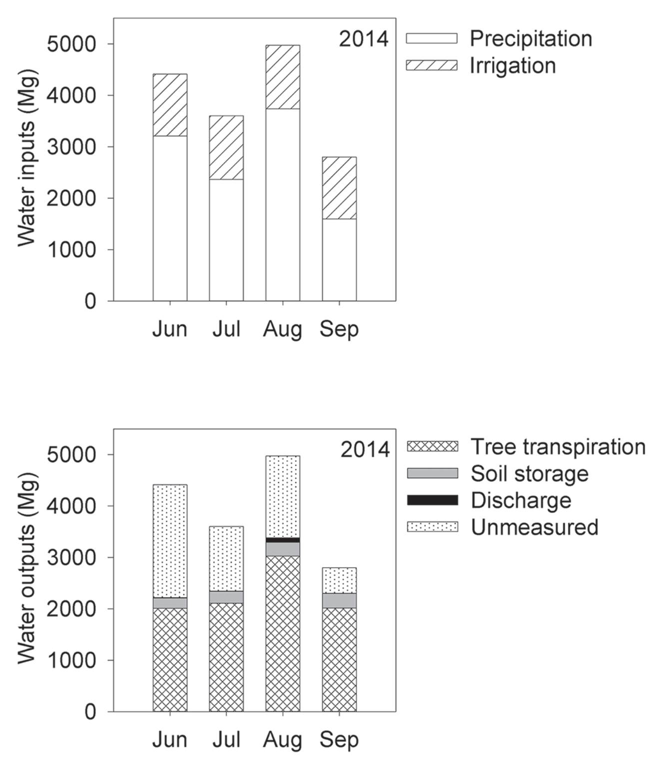

Fig. 6. Monthly total inputs (precipitation and irrigation) and outputs (tree transpiration, soil storage, discharge, and unmeasured) for The Morton Arboretum parking lot during June through September 2014.

quantitative data are available documenting specific impacts of trees on water cycling in green infrastructure systems (Bartens et al., 2008). We addressed this gap in the literature by measuring g_s for bioswale trees and modeling total transpiration such that we could infer the ability of trees to contribute to bioswale function.

The results show increased g_s for trees planted in bioswales was observed on two of eight measurement dates, both later in the growing season. The reason for this elevated g_s is not a greater supply of soil moisture (Fig. 2), so it must be related to increased atmospheric demand for water. Because no atmospheric factors were measured during this experiment, we can only speculate that the air in the immediate vicinity of the bioswales had comparatively low relative humidity. The 3-m-wide bioswales were surrounded by 2 ha of permeable pavement parking lot and thus were likely to have relatively low atmospheric humidity (Cui and Shi, 2012). This would have led to a higher water vapor concentration gradient between the leaf surface and the air and thus higher transpiration, a physiological response that trees have previously demonstrated in paved environments (Kjelgren and Montague, 1998).

Irrespective of the causal mechanism, the knowledge that g_s (and thus transpiration) for trees in bioswales was equal or greater to that of trees planted outside the bioswales suggests that trees contribute to bioswale function by transpiring absorbed soil moisture. But to what extent did their contribution affect the bioswale's water balance? Our findings suggest that trees are very active in the water cycling of a parking lot. Transpiration by trees accounted for 46 to 72% of total water outputs from the system. This clearly demonstrates that trees are an integral component of the green infrastructure system and function to reduce runoff and discharge from the parking lot.

These results corroborate previous field studies of tree function in bioswales (Read et al., 2008) but stop short of distinguishing between the suitability of different tree species for bioswales. To answer the latter question, this research explored species-specific g_s responses for trees planted inside and outside bioswales. The observed variation in g_s among species hints at variable species suitability for inclusion in bioswales; that is to say, not all species will contribute equally to bioswale function. Results from Experiment I show that *Q. macrocarpa* had greater g_s than the six other species, but total tree transpiration also depends on total leaf area. As such, trees with large mature size (e.g., *Q. macrocarpa*) are likely to contribute greater functional value to bioswales by transpiring more. Such potential for elevated transpiration is highly desirable in a bioswale because stormwater management function can be improved if temporarily stored rainfall can be rapidly cycled back into the atmosphere. Results also showed that *C. canadensis* exhibited lower g_s within the bioswale compared with conspecific trees outside the bioswale. This low g_s combined with the relatively small mature size of *C. canadensis* allows us to infer that this species will not contribute to bioswale function as well as *Q. macrocarpa*. To generalize, bioswale design incorporating trees must consider the rate of transpiration and the mature size of the chosen species if optimizing bioswale function is a desirable outcome.

A final consideration must be tree condition and health. Species with optimal functional and growth potential must be able to survive in bioswales if they are to contribute long-term hydrological benefits. Results from Experiment II show that the *Ulmus* genera had the most rapid diameter growth rate of all species studied and actually grew faster when planted in the bioswale. Greater bioswale growth rate was also observed for *Cercis*, *Fraxinus*, and *Gymnocladus*, whereas all other genera grew at the same rate as their analogs outside the bioswale. This relatively high growth, combined with the fact that no genera had lower tree condition index scores in the bioswales, suggest that the bioswale environment did not present a stressful environment for the species we studied.

Aside from possibly electrical conductivity in both bioswale and null environments, the soil conditions did not appear to negatively influence tree growth and health. We observed a negative correlation with tree g_s to confirm this assertion. Bioswales and null environments did not differ regarding soil electrical conductivity, suggesting that, in this study, both were susceptible to contamination by deicing materials. High salinity was expected and is common in the midwestern United States due to routine application of road salts to control ice and snow. Elevated soil salinity from these salts has been found to negatively influence urban tree performance (Kelsey and Hootman, 1990).

It is important to note that our results only cover seven genera at a single site. We do not suggest that all tree species will be healthy in bioswales. We do, however, believe that it is likely that trees are among the best adapted growth forms for bioswales because their large, spreading root systems are opportunistic and develop preferentially where resources are available (Zanetti et al., 2011).

Conclusions

Here we demonstrate that bioswale trees are of critical importance for reducing runoff and discharge in a parking lot. By measuring stomatal conductance and modeling transpiration, we estimate that trees accounted for 46 to 72% of total water outputs from bioswale systems. Our results demonstrate the integral role of trees as components of the green infrastructure system. We provide data showing that not all tree species are equally suited for bioswales in terms of their condition, growth, and potential functional value. We determined that the contribution of trees to bioswale function was influenced by three factors: (i) the rate of stomatal conductance, (ii) total leaf area and mature size of the tree, and (iii) the health and condition of the tree. This research may hope to set an agenda for future research on the topic of trees, bioswale design, and bioswale water balance modeling. We suggest two areas for future research: (i) systematic explorations of the physiological and morphological traits various tree species might possess to make them more or less suited to bioswale environments and (ii) a long-term analysis of tree health and condition in bioswales in relation to the hydrological cycle.

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