CONSIDER THE SHRUB: ECOLOGY AND DESIGN IN PARKING LOTS

By

JENNIFER RYAN

A thesis submitted to the

Graduate School-New Brunswick

Rutgers, The State University of New Jersey

In partial fulfillment of the requirements

For the degree of

Master of Landscape Architecture

Graduate Program in Landscape Architecture

Written under the direction of

Jean Marie Hartman

And approved by

____

____

____

New Brunswick, New Jersey

May 2017

ABSTRACT OF THE THESIS

Consider the Shrub: Ecology and Design in Parking Lots

by JENNIFER RYAN

Thesis Director:
Jean Marie Hartman

Parking lot designs depict large trees planted with the expectation that they will provide the ecological services of stormwater capture, cooling the air and shading. Yet, the harsh growing conditions in parking lots, including soil compaction, limited water access and high heat, limit the growth of the trees. How do these harsh conditions effect tree ecological function? Do shrubs, which are less costly and easier to replace, provide ecological function and are they limited by parking lot conditions as well? This study assessed tree and shrub transpiration over the course of growing season to understand plant water relations. Of the three tree species, transpiration at the leaf scale was not correlated to location in parking lot versus park setting, but trees were significantly smaller and less healthy in parking lot settings, which reduced canopy scale transpiration. Conversely, three out of four shrubs were affected by the location in parking lot versus the park setting, but size and health were similar. A parking lot design was made that showcases planting typologies

appropriate to the amount of water infiltrating to the soil. Incorporating stormwater management, this design demonstrates the necessary infrastructure changes needed for full growth of trees which maximizes ecological services in a relatively small footprint.

Acknowledgements

Thanks to all those who helped make this thesis:

To my committee—Jean Marie Hartman, Jason Grabosky, and Tobiah Horton—for expertise, patience, and critique. To Jean Marie especially, for her patient optimism during the dark days of thesis muddling.

To my classmates for cheerleading and advice.

To my family for support and love.

To Maizie, go Team Shrubbery!

To Winifred, without you, this would not exist.

Table of Contents

List of Tables

List of Illustrations

Chapter One: Introduction

Standard parking lot design often entails large expanses of asphalt punctuated by trees in pits or strips that cap ends of parking bays or guide cars through the lot. Frequently, the number and spacing of trees follow local building ordinances that specify trees per number of parking spaces (Figure 1) or amount of shading within a specified time.[1] For example, the Borough of Princeton in New Jersey requires 1 tree for every 3.4 spaces of off-street parking.[2] Prince George's County, Maryland requires 1 tree for every 300 square feet of interior parking space in a parking lot.[3] Shrubs are generally discussed as a way to screen the view of cars from the street.[4]

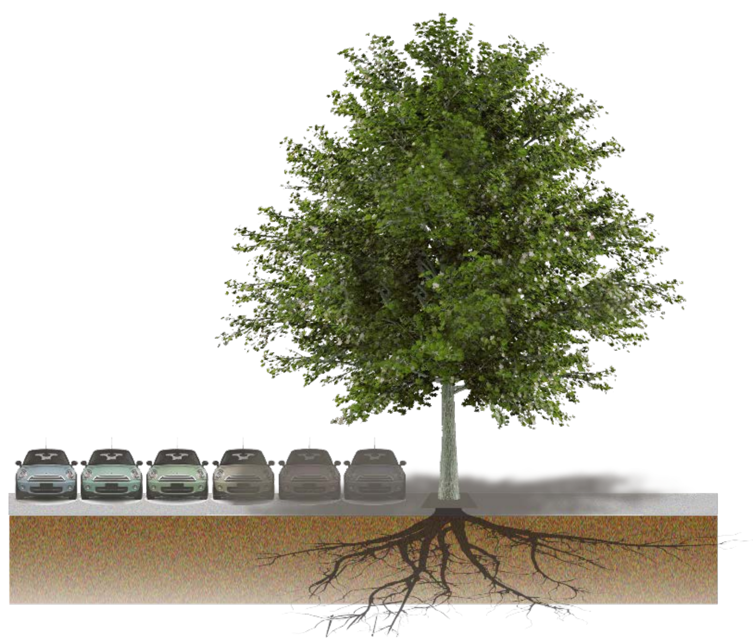


Figure 1: Trees are planted according to local ordinances that specify the number of trees per parking spaces.

Ordinances require trees to be planted in parking lots because of the many ecological services potentially provided, including filtering air pollution, sequestering carbon, providing cooling shade, and capturing stormwater. Numerous studies back these assertions: Trees and shrubs removed 711,000 tons of five airborne pollutants in a one year study, which provided annual value of $3.8 billion.[5] Average carbon storage in trees in urban Minneapolis counties was 33.43 million kgC/year.[6] Temperatures under trees were 12° C lower than the surrounding concrete surface temperatures and 5-7° cooler in globe temperature—a measure of temperature which accounts for convection and radiation, and mirrors a human's feeling of temperature.[7] The area under trees was cooler than sites that were exposed or covered with shade cloth in a study in Israel.[8] Additionally, tree shade significantly reduces the maintenance and concomitant costs of asphalt in a California study.[9] Impervious asphalt parking lots with tree pits reduced stormwater runoff by 60% compared to non-vegetated asphalt.[10]

The larger a tree grows, the larger the scale of the service provided. In a study of Chicago urban trees, larger trees (greater than 46 cm or 18 in diameter at breast height (DBH)) absorbed 60-70 times more pollutants than smaller trees (less than 15 cm or 6 in DBH) and sequestered 90 times the amount of carbon.[11] A tree requires at least 30 years to reach mature size before it begins to provide the shading and stormwater management benefit depicted in designs.[12] Parking lot designs generally depict trees that have reached full canopy, which, while allowing designer and client to visualize the amount of space needed for the full size of the plant, distorts reality.

Despite optimistic predictions of parking lots fully shaded by trees, many trees do not reach full canopy in the harsh conditions of the built environment.[13] The inhospitable heat and wind, constricted growing space of the standard tree pit, compacted soil, and reduced ability to access water and transpire often restricts the growth of trees and leads to early decline and death (Figure 2).[14] Other reasons for a trees decline may be nursery cultural practices[15] or damage to trees with mowing equipment.[16]

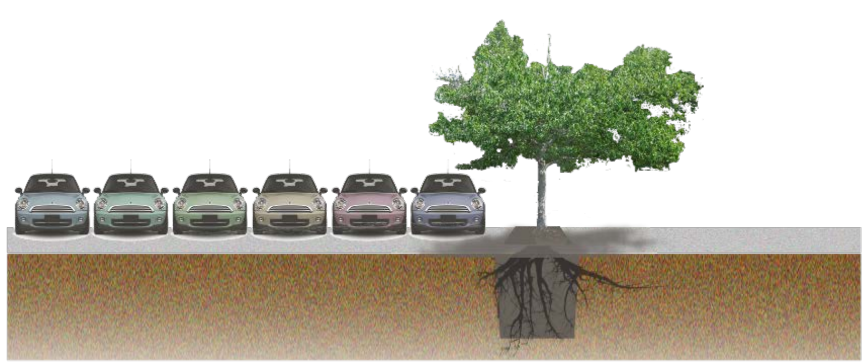


Figure 2: Trees in parking lots are often smaller than expected.

The findings described above generate many questions, such as: How does size of planting pit effect the ability of a tree to provide expected ecological services of stormwater capture, cooling and shading? How do shrubs, which are less costly and more easily replaced, function ecologically in parking lots? Are shrubs affected by the size of the planting pit, as trees are?

One way of understanding how trees and shrubs are providing ecological services is to assess their transpiration. Transpiration is the release of water into the atmosphere through a plant's stomata (sing. stoma), which are tiny holes that are most prevalent on the underside of plant leaves (Figure 3). The holes are openings between two specialized cells, called guard cells, and can be closed to control gas exchange. A complex interaction between light, available CO_2, water, humidity, and hormones creates a pressure differential in water in the guard cells, which distorts the shape of the cells and thus opens or closes the stoma. Plants release large amounts of water per year through transpiration, but use only 5% of the water they absorb for energy production and other uses.[17]

Transpiration

Transpiration is a measurable indicator of a plant's health and function: having adequate water allows the stomata to open for transpiration and photosynthesis. If there is a dearth or surplus of water to transpire, the plants close their stomata and subsequently cannot absorb CO_2 to produce energy.

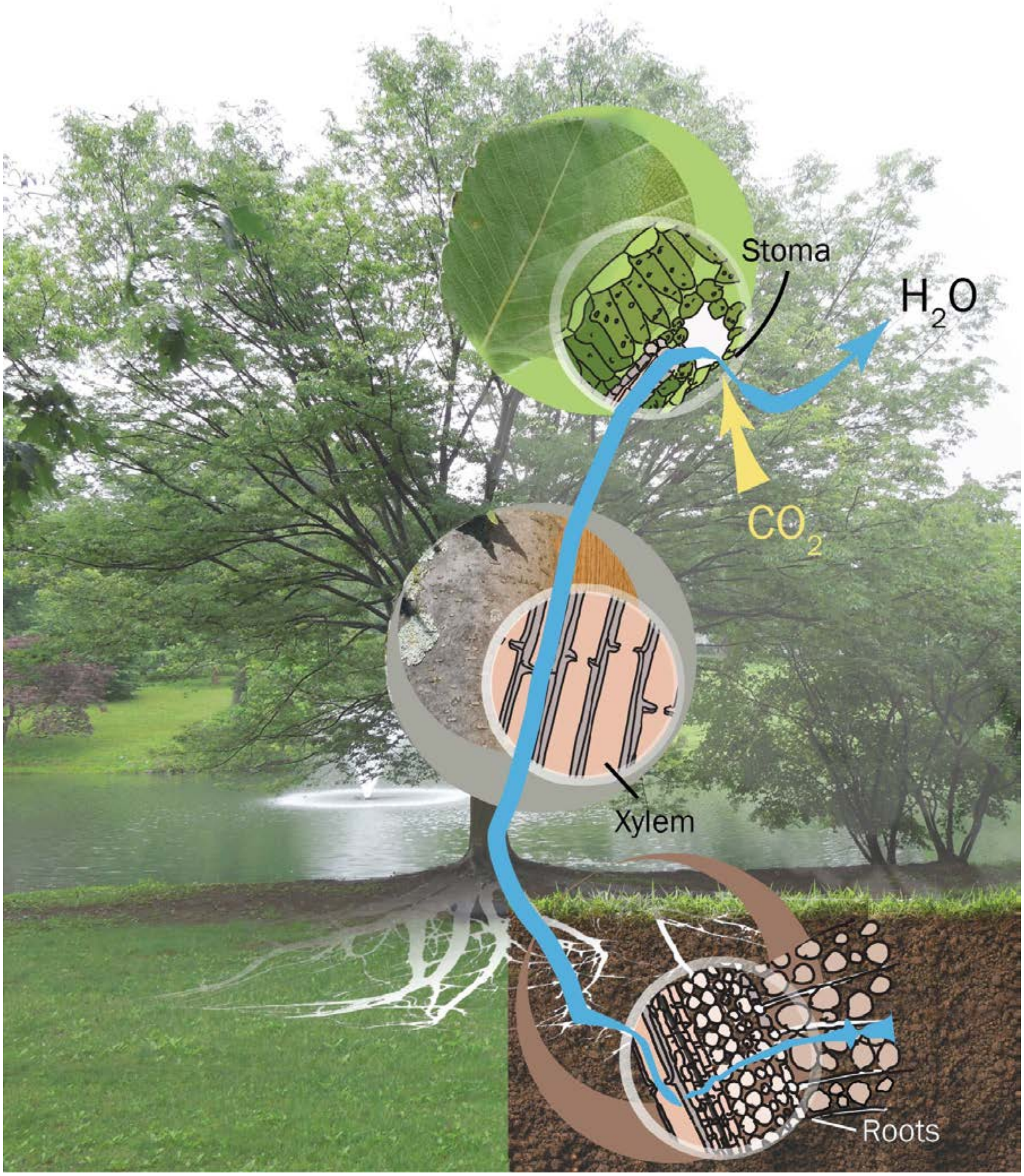


Figure 3: Transpiration and water movement through plants.

Furthermore, with too little or too much water, the plant cannot maintain turgor pressure in the cells and wilts. Even though the plant has wilted, it may still be absorbing water, but not enough to produce energy. While trees vary in their water needs and have different tolerances for drought stress, water deficit—when lack of water and loss of turgor pressure reduce the ability of the plant to function—causes embolisms of xylem vessels and cellular damage, which are not immediately repaired after water becomes more available.[18]

Transpiration is also an important means of leaf cooling in plants. The dark pigment in the leaf absorbs more radiant energy than the amount used for photosynthesis and other chemical reactions. This surplus raises the temperature of the leaf, which is then cooled by vaporizing water from the leaf. The rest of the heat is released by convection to the air. Water is released in two stages: first, from the cell walls into substomatal air spaces and then from the substomatal space into the atmosphere.[19] This process also cools the surrounding area and mitigates the high heat in paved areas.[20] During periods of drought, tree leaves can overheat, causing damage to chloroplasts.[21]

Transpiration is governed by a complex interaction of humidity, vapor pressure deficit, radiation, temperature and amount of water in the soil and ability of the water to move in soil.[22] Water is also lost from soil surfaces and, combined with transpiration, this process is known as evapotranspiration (ET) Young trees or shrubs surrounded by large amounts of bare soil lose more available water through surface soil evaporation than through transpiration, while older trees with large canopies lose more water through transpiration.[23]

Water movement through the plant is explained by the Soil-Plant-Atmospheric Continuum, in which a gradually increasing negative force pulls water from the soil through the roots, up through the stem, into the leaves and out into the atmosphere.[24] Water potential (Ψ), the pressure required to move an amount of water, provides one facet of the complex system of transpiration, and predicts the direction and rate of flow and the amount of water available in the soil. Total water potential (Ψ_T) depends on a synergy of matric potential (Ψ_m), osmotic potential (Ψ_o), pressure potential (Ψ_p) and gravitational potential (Ψ_g). Water potential is measured in units of pressure—megapascals (MPa) which is 1,000,000 pascals, or one newton per square meter, which is the force needed to accelerate one kilogram at a rate of 1 m/s^2. [25]

Pressure potential is the positive pressure of the cell membrane against the cell wall. This force—turgor pressure—supports the leaf in woody plants. When the pressure in the leaves goes down due to lack of water (or too much water, diseases, or pests) and accompanying changes in the solute ion gradient, the leaf wilts. Gravitational pressure is the force of gravity on water in the plant and soil and is generally considered to be a constant when discussed in plant studies.[26]

Matric potential is a negative force that, in plants, occurs as a result of hydrogen bonding of water to surfaces such as soil particles, cell walls, and xylem tube walls. Matric potential is evident in the hydrogen bonding of water to soil particles in layers which fill the micropores of soil (and macropores if the soil is saturated). The first layers of water have a very strong bond to the particle, with each subsequent layer having less adhesive intermolecular forces until gravity pulls water down to the water table. About half the water bonding to soil particles is available to plant roots, which exert a negative pressure through root manipulation of the osmotic gradient.[27] As roots absorb mineral ions from the soil, a lowered osmotic potential exerts a force to pull water into the roots. Casparian bands in roots prevent the return flow of water to the soil. Continued mineral absorption guarantees continued water flow[28]. Water moves through the plant using a mixture of osmotic and matric forces, always with a lower potential than the preceding part. For example, if roots have a potential of -1 MPa, stems can be in the range of -2 MPa and leaves at -3 MPa and dry air can be at the atmospheric pressure of -100 MPa.[29]

The additional force of capillarity, which combines the adhesive quality of water and polar groups, surface tension due to this adhesive quality and gravitational force, all act on water's movement through xylem tubes. Water molecules bonded to the xylem tube walls (tracheids or vessels) continue to flow upward and the strong cohesive forces of water molecules pull water up until gravitational forces stop the waters rise. The thinner the tube, the higher the water rise: a tube of 50 μm diameter will rise to a height of about 0.6 m, while a larger tube of 400 μm diameter will rise only .08 m.[30]

There are several methods for measuring transpiration in trees, including lysimeters, thermometric sap flow gauges, porometers which measure single leaf infrared gas exchange, or chambers to measure whole plant infrared gas-exchange. These methods have benefits and drawbacks[31] including difficulty scaling to whole tree water use.[32]

Transpiration levels vary by species of woody plant and depend on the time of day or year, as well as the type of tree and amount of leaves.[33] Sap flow generally is low at night, begins to rise after sunrise, peaks at noon and drops sharply after sunset,[34] though trees do continue to transpire nocturnally.[35] In temperate climates, water flow through deciduous trees is very low when no leaves are on the tree, but has large spikes when trees are in full leaf. Coniferous trees tend to have a steady amount of water flow throughout the growing season.[36]

Not all leaves transpire the same amount on a tree. Shaded leaves release approximately half the amount of water than sunlit leaves,[37] as leaves receiving direct solar radiation need more cooling than shaded leaves. Leaves of plants that are native to arid climates tend to have a higher water use efficiency (ratio of water transpired to CO_2 uptake).[38] Trees with more leaves conduct more water, even in densely paved areas.[39]

The amount of water available to a tree is relative to the amount of water used. More paving around a tree increases temperatures and the amount of solar radiation, and lowers air humidity.[40] Higher amounts of paved root area is correlated to lowered ability to conduct water, photosynthesize and access nutrients.[41] Increased water infiltration provided by permeable paving did not increase the amount of transpiration in first year tree plantings compared to impervious pavement, though heavy clay soils may have decreased the amount of infiltration possible.[42]

The size of the growing area for a tree pit is correlated to the mature size of a tree.[43] Providing trees with adequate soil volume and water allows trees to grow to full spread at maturity. Numerous equations to calculate the appropriate soil volume needed for maximum growth in trees in urban settings have been postulated. Lindsey and Bassuk[44] developed an equation to estimate the total water needs of urban trees to reach full growth potential in order to recommend an adequate, but economically practical soil volume size. This equation multiples the crown projection of the tree by the Leaf Area Index, the highest mean daily evaporation, and the tree transpiration ratio to find the daily tree water use. This figure is then multiplied by the average number of days between local rainfall and divided by the available water holding capacity of the soil to find the volume of the tree soil pit. Bed dimensions are then extracted from this volume. DeGaetano[45] further expanded Lindsey and Bassuk's equation to include local climate daily evaporation rates while calculating water needs for container grown trees. Trees in urban areas can be considered containerized plants considering the amount of compacted soil, concrete and infrastructure that limits the spread of their roots.[46]

Measuring plant transpiration can provide clues to factors that contribute to reduced plant growth. Studies that compare transpiration of trees planted under various surfaces find increased or decreased transpiration. Three species planted under various surfaces did not use more water across treatments.[47] *Gleditsia triacanthos* transpired more than same species trees in rural locations, presumably due to higher temperatures.[48] Some trees have better adaptations for hot dry environments—in Tokyo, conductance was measured over 3 years in 3 species of tree growing in street and park conditions. Street trees avoided hydraulic failure—were able to recover from severe water stress--through stomatal closure at high water leaf potential.[49]

This study aimed to quantify the transpiration of common parking lot trees and shrubs with limited water access due to impermeable surfaces and constricted root zones and corresponding plants in more park like settings;

analyze the effect of limited water access and weather on transpiration rates in these settings; and understand implications of tree pit design in harsh environments on tree growth and stormwater uptake.

Chapter 2: Methods

Transpiration in trees and shrubs was compared between park like settings and parking lots in Middlesex County, New Jersey, USA. This county in Central New Jersey is characterized as urban/suburban with much of the land cover developed and high automobile traffic—over 21 million Vehicle Miles Travelled (VMTs) in 2015.[50] The area tends to be warmer than surrounding parts of the state due to the concentration of developed areas that result in the heat island effect, and tends to have 30-40 more days over 32 °C (90 °F), than less developed areas of the state. Temperatures can range from 37 °C (100 °F) or higher in the summer to below -17 °C (0 °F) in the winter with an average temperature of 12 °C (53 °F). The average rainfall is 124.5 cm (49 inches) per year, with measureable precipitation on about 120 days of the year. Fall is the driest time of year with 8 days of precipitation per month, compared to 9-12 for the other months of the year.[51]

High temperatures in the summer increase evapotranspiration rates which lead to reduced soil moisture, resulting in a cycle of decreasing soil moisture and increased temperatures. Over time, elevated temperatures can then induce drought stress in plants as they struggle to extract water from the soil.[52] Plants that grow in New Jersey exhibit a wide range in their tolerance of temperatures and soil moisture.[53] The average day of last frost is April 15th and the average first frost is October 15th. The planting zone is 7a-5.[54] (Figure 4 and Figure 5)

Figure 4: USDA Plant Hardiness Zone Map: Northeast Region, 2012. The white circle indicates the study area in Zone 7a. Map by US Department of Agriculture, 2012.

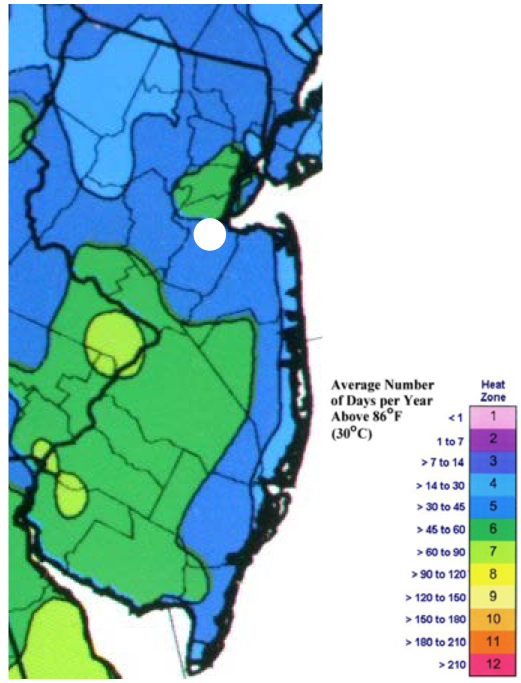


Figure 5: AHS Plant Heat Zone Map, 2017, New Jersey. The white circle indicates the study area in Zone 5. Map courtesy of American Horticultural Society, 2017

Vegetation in this region straddles the Piedmont and Inner Coastal Plain physiographic regions, but is mostly characterized by ornamental plantings typical of a suburban area. The plants selected were common plantings in local parking lots and included trees: *Acer rubrum* (Red Maple), *Gleditsia triacanthos var. inermis* (Thorness Honeylocust), and *Zelkova serrata* (Japanese Zelkova) and shrubs: *Euonymous alatus* 'Compacta' (Winged Euonymous), *Ilex glabra* (Inkberry Holly), and *Spiraea japonica* 'Gold Mound' (Gold Mound Spiraea). *Rosa rugosa* (Saltspray Rose) is a rather novel plant in parking lots in this region, but as a highly tolerant plant was selected for this study. All selected species are considered tough plants adaptable to a range of conditions and not as likely to decline by disease or cultural conditions (by contrast, *Quercus* sp. are being affected by Bacterial Leaf Scorch and high pH soils found in parking lots, *Pyrus calleryana* tends to break apart).

Parking lots and park like settings were located on Rutgers campus and in a Costco parking lot (Figure 6 to Figure 13), which limited the variability in construction and maintenance techniques of the tree pits and planting beds. Strips had root restriction on two sides, while pits had restriction on four sides, either by pavement edge or the root system of another tree. Tree pits on campus were installed after construction and paving of the parking lot, and were less than 1.2 meters (4 feet) across the top when excavated (Clemson, pers. com. 2016). The park like settings were in grassy areas of campus that included Livingston Quad, Busch Campus, Cook Campus and Rutgers Gardens, and all had similar maintenance regimes. Park like conditions had no restriction to their roots or minimal restriction on one side (i.e. planted near a pond or next to a sidewalk, but not under the dripline).

Nine replicates of each tree species were identified, that were at least ten years old. Of these nine, three were growing in an unrestricted park-like setting, three in a parking lot strip and three in a parking lot pit. Shrubs were of

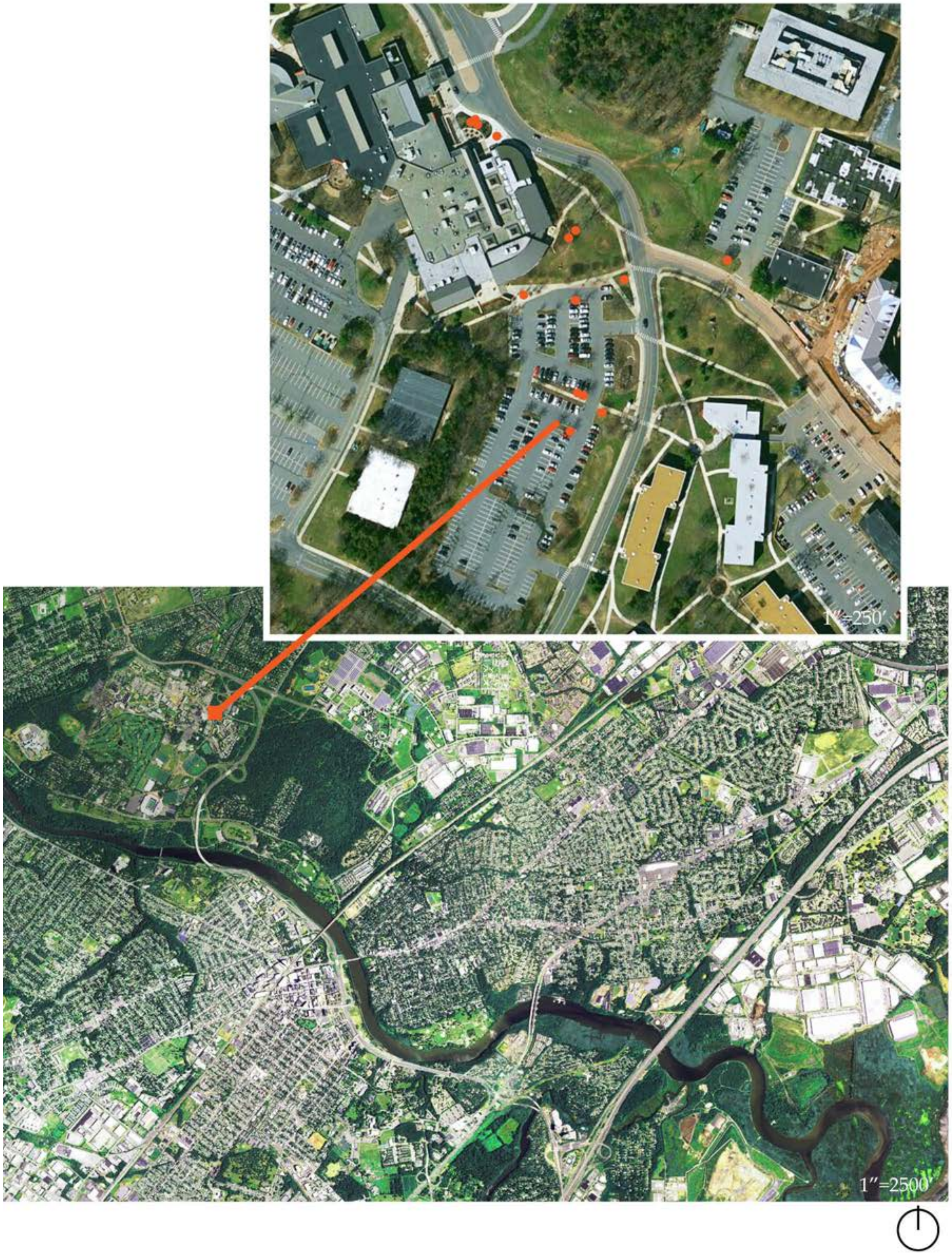


Figure 6: Trees and Shrubs in Lots 67B, 63A, and at Busch Student Center, Rutgers, Busch Campus. Map from Google Earth, 2017.

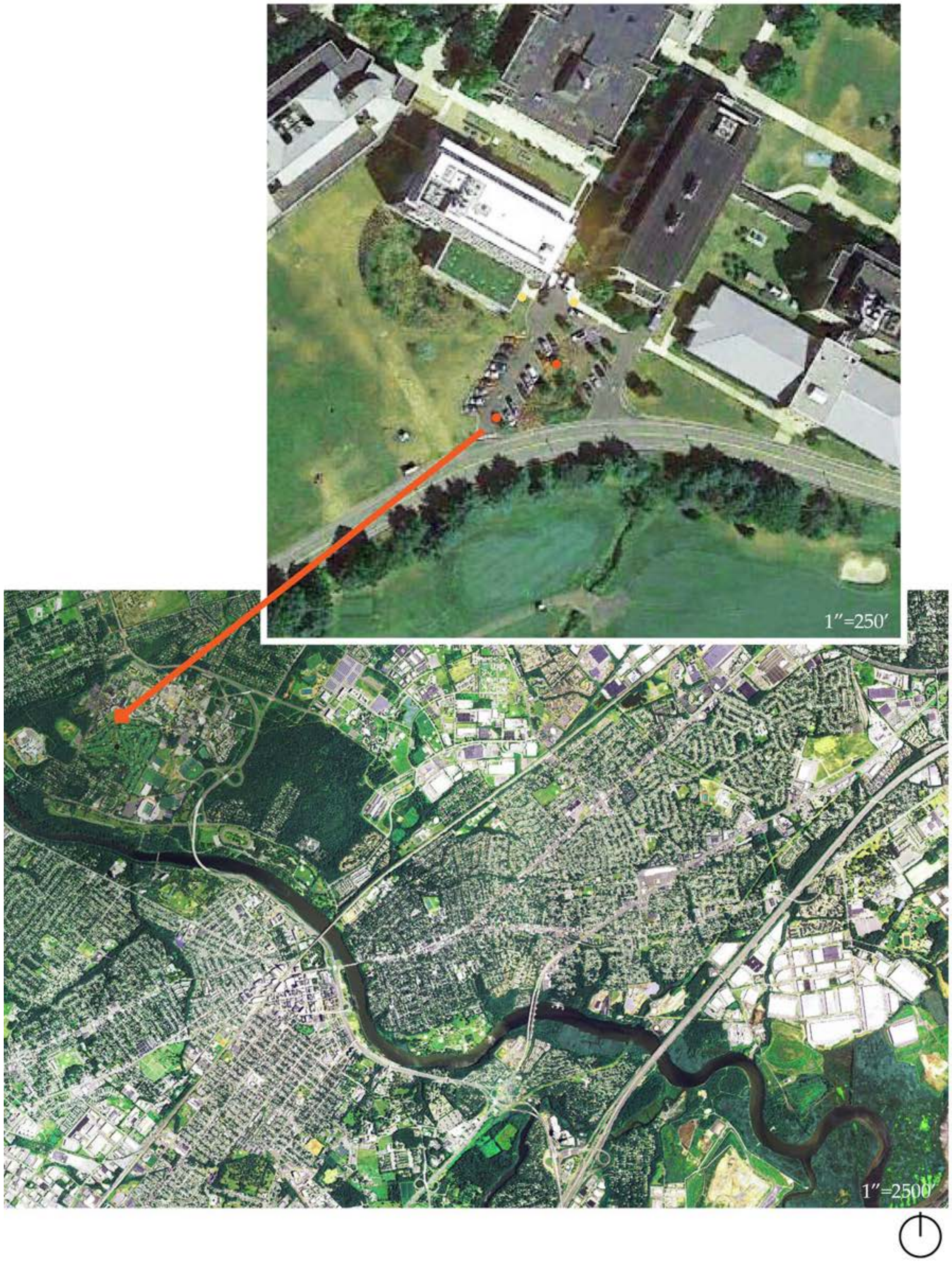


Figure 7: Trees in Lot at 170 Frelinghuysen Rd., Rutgers, Busch Campus. Map from Google Earth, 2017.

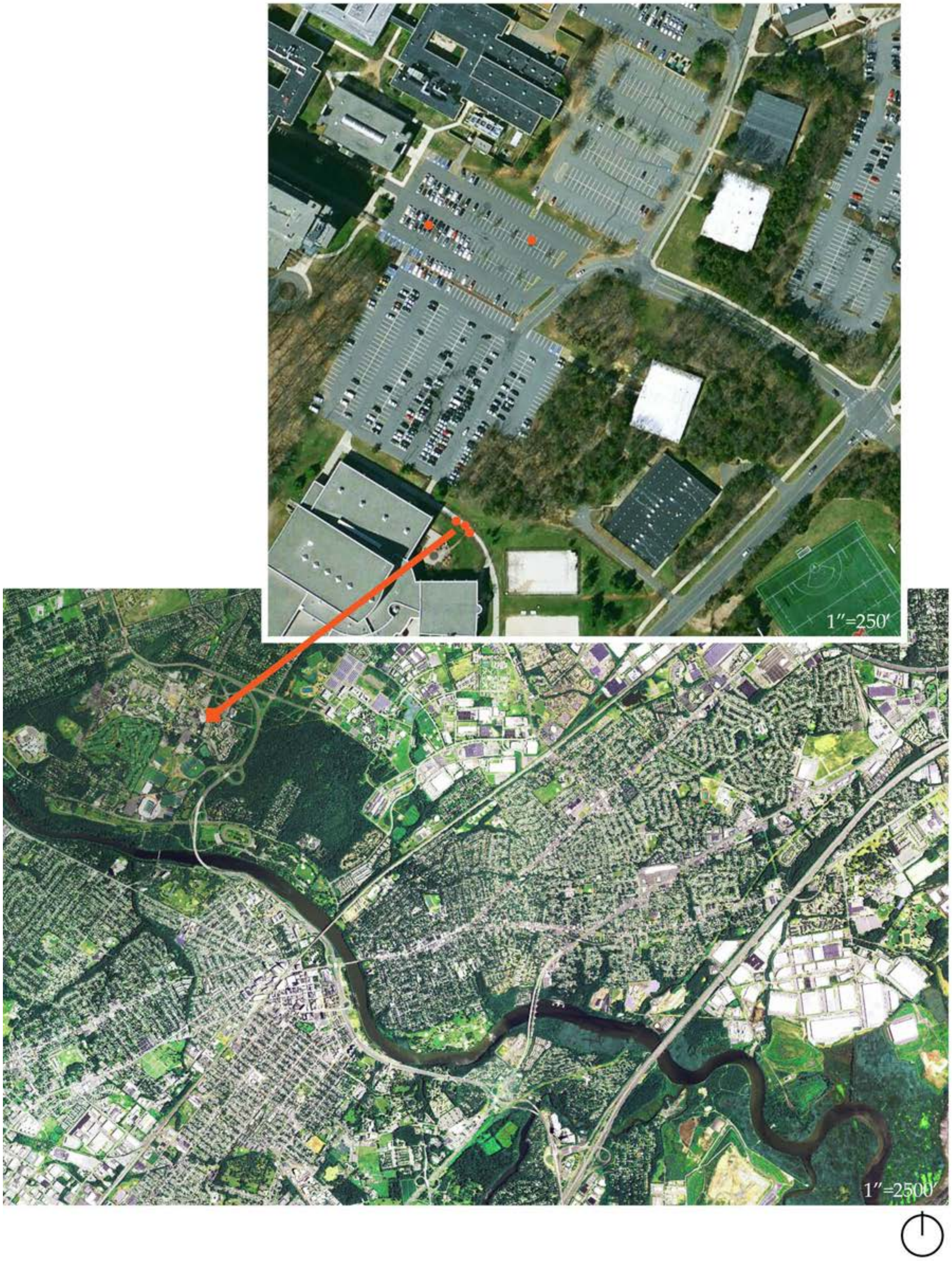


Figure 8: Trees and Shrubs in Lot 60A and at Werblin Recreation Center, Rutgers, Busch Campus. Map from Google Earth, 2017.

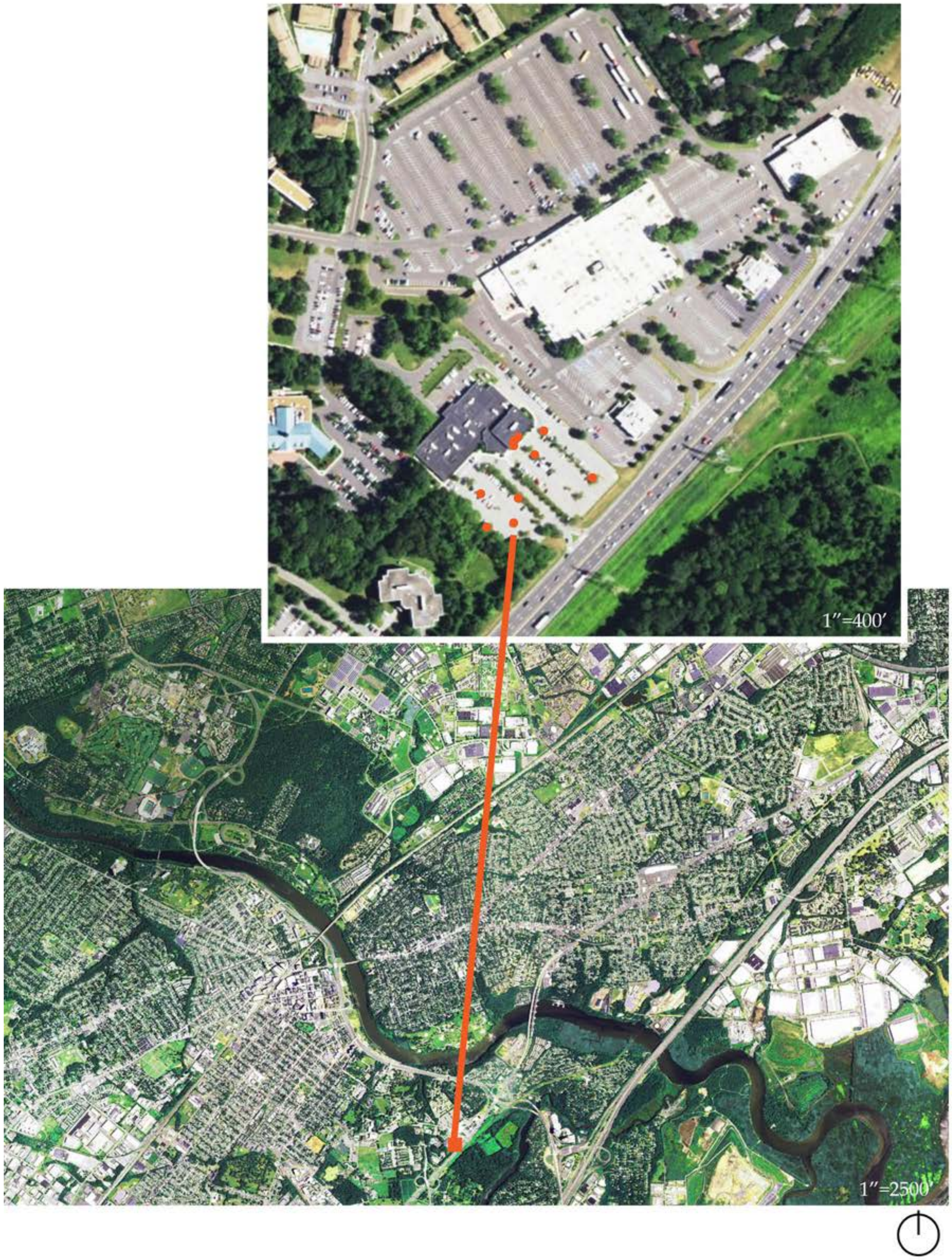


Figure 9: Trees and Shrubs in Lot at ASBII, Rutgers, Cook Campus. Map from Google Earth, 2017.

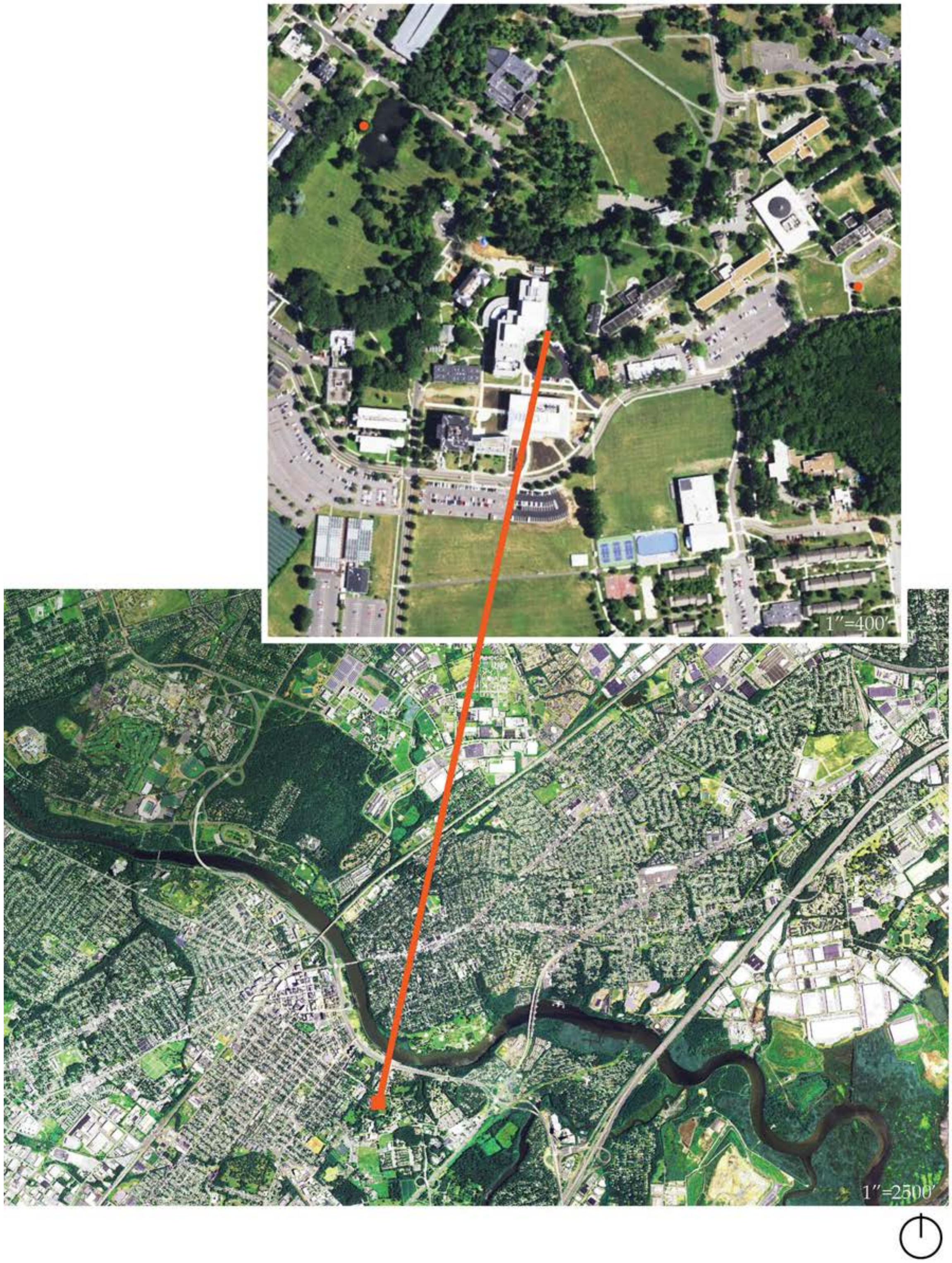


Figure 10: Trees at Passion Puddle and Lippencot Hall at Rutgers, Cook Campus. Map from Google Earth, 2017.

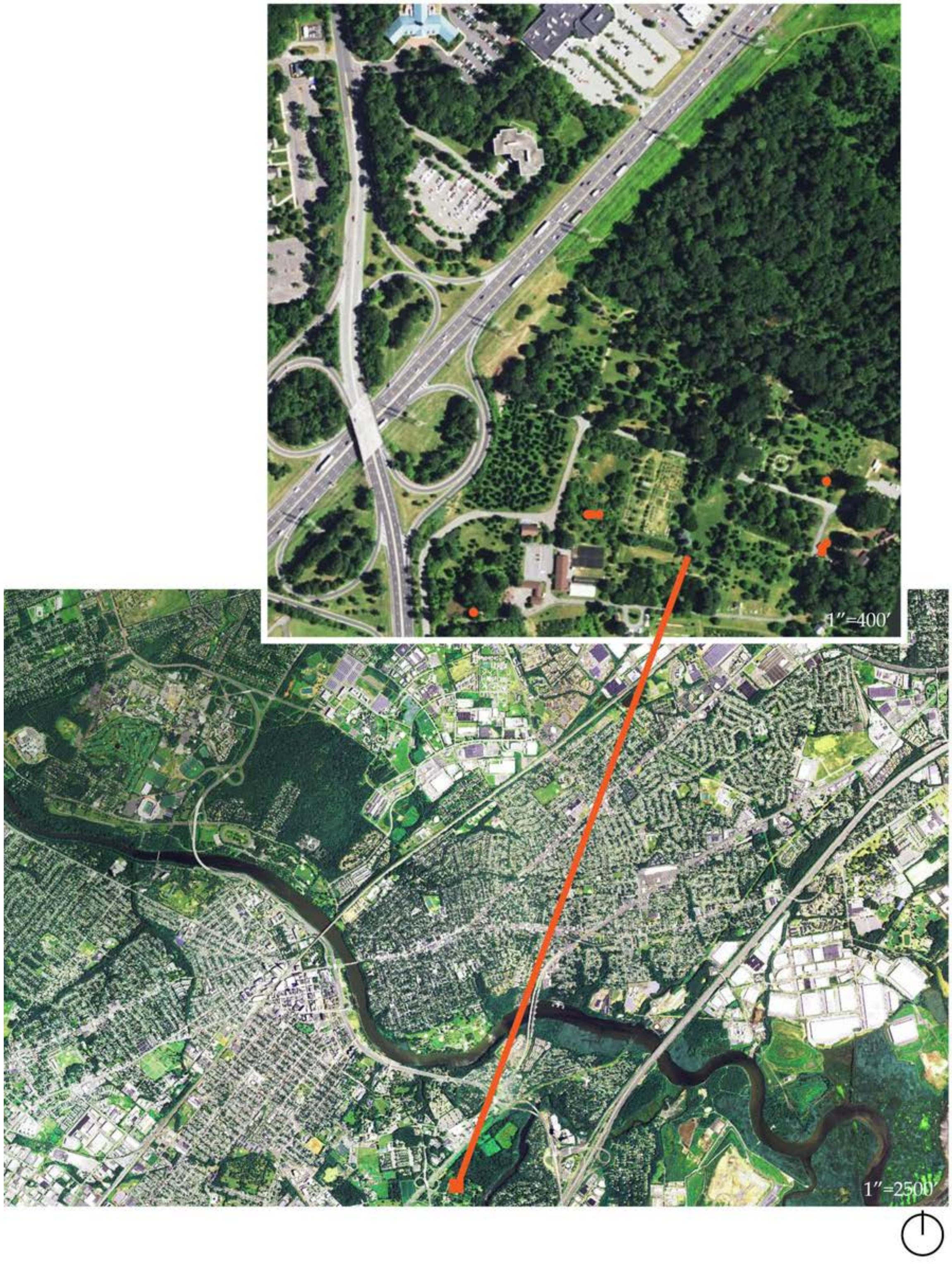


Figure 11: Trees and Shrubs in Rutgers Gardens, Rutgers, Cook Campus. Map from Google Earth, 2017.

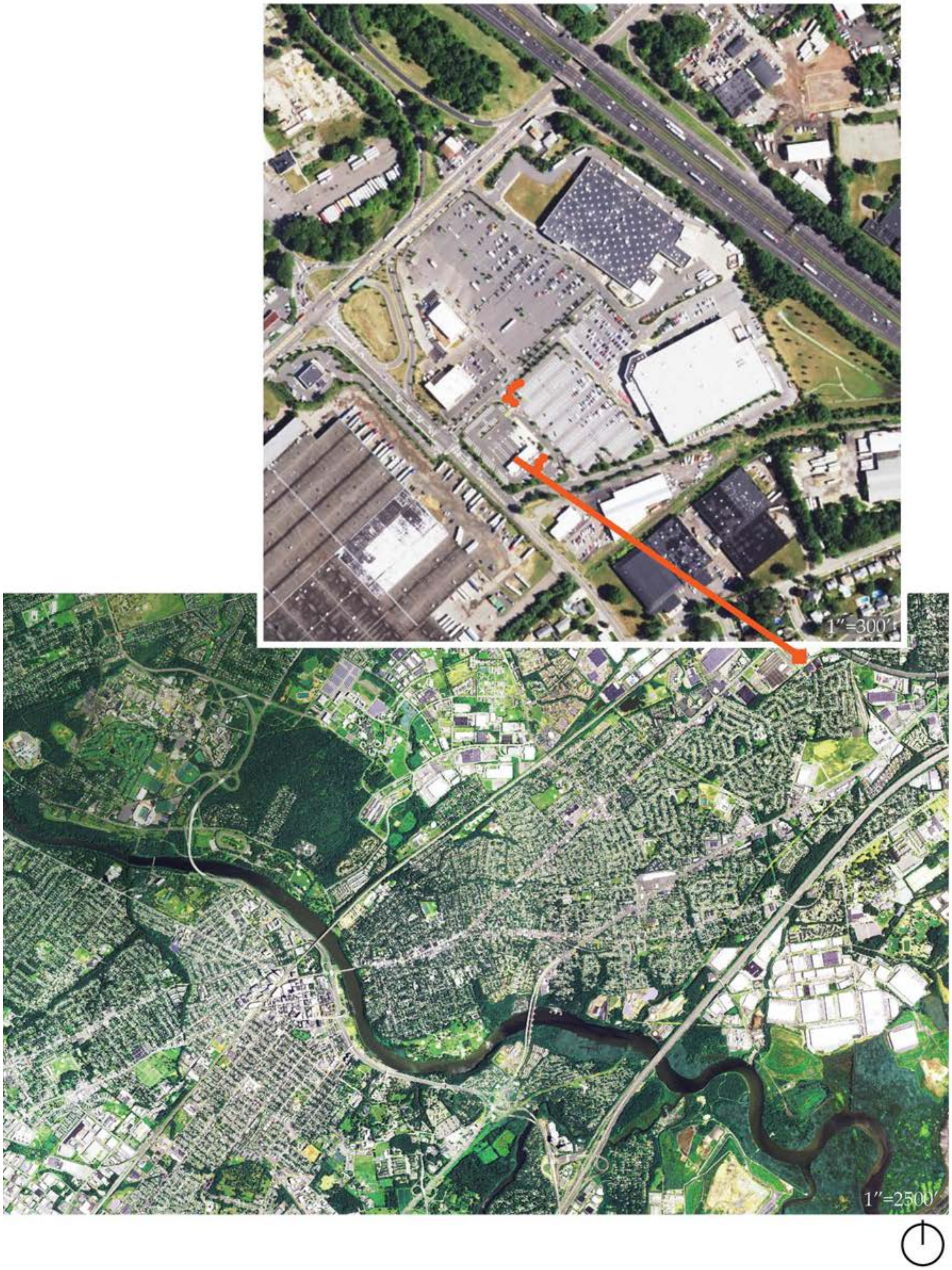


Figure 12: Shrubs at Costco, Vineyard Road, Edison, NJ. Map from Google Earth, 2017.

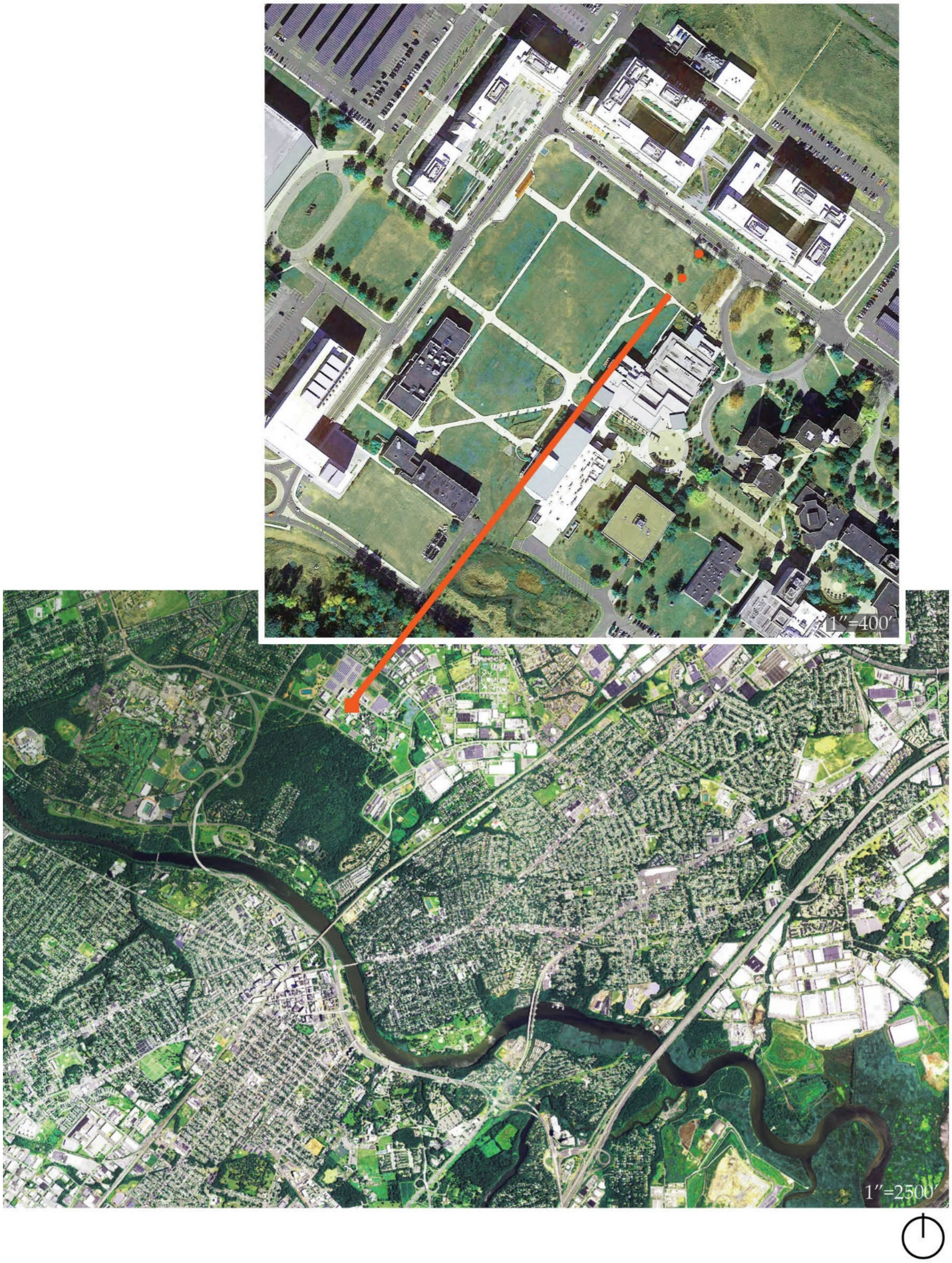


Figure 13: Trees near Livingston Student Center, Rutgers, Livingston Campus. Map from Google Earth, 2017.

indeterminate age. For each species, six replicates were chosen—three in a park like setting and three in a parking lot strip. Shrubs had a similar size and had not been excessively shaped or pruned at the beginning of the growing season.

Trees in parking lots tended to be much smaller than trees in park like settings. To ensure that transpiration measurements were from the healthiest trees in all settings, plants were assessed with the Urban Tree Health Index,[55] a rating system for evaluating observations of five parameters of tree health. Using a Likert scale, the opacity, vitality, quality and growth of twigs and leaves and the proportion of tree height to live crown was rated. Scores were normalized according to species. For example, *Gleditisia triacanthos* tends to have a low crown opacity, while *Zelkova serrata* tends toward high crown opacity. Likert scale deviations were tallied and used to assign a final health score of Fair, Poor, or Critical. Those with no deviations were labelled Healthy.

Transpiration was measured every one to two weeks using a LI-COR 6400XT Portable Photosynthesis System (LI-6400),[56] which analyzes gas exchange at the leaf level and calculates transpiration from CO_2 uptake and condensation release. Three fully unfurled leaves in full sun or partly cloudy days were measured from each specimen during the prime growing season of June to August. Shrub leaves were sampled while still attached to the plant, and tree leaves were either sampled on the tree or excised, retrimmed under water, and sampled while in a container of water. Measurements were taken at PAR=1500 μmol, and temperature 26 to 30 degrees C (78-86 F).

Most of the tree and shrub leaves were large enough to fill the chamber of the LI-6400—a 6 cm^2 area. Those that were smaller than the chamber—i.e. *Gleditsia triacanthos* and *Ilex glabra*—needed adjustment to the leaf area. These leaves were photographed under a replica gasket of the same size (Figure 14), then, using Photoshop, pixels within the total area of the gasket and the leaf were counted. These measurements were used to calculate the reduced leaf area in the chamber, which was then used to calculate the actual photosynthesis and condensation.

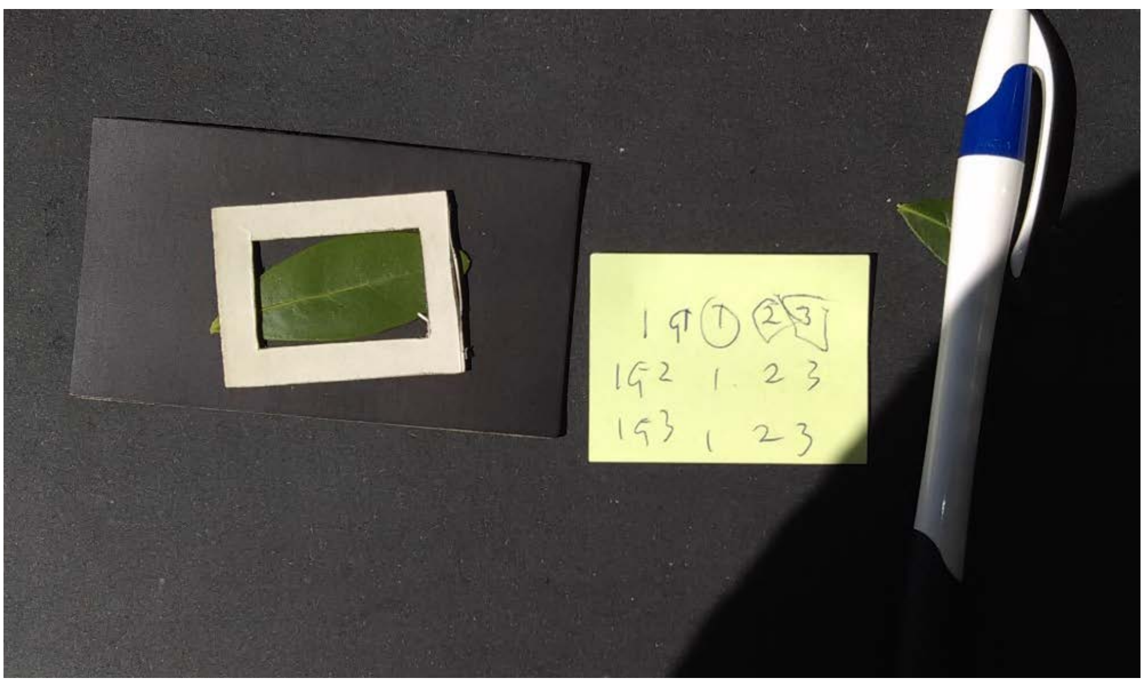


Figure 14: Photograph of leaf used to find ratio of leaf to cuvette area in LI-6400. Photo by author

Transpiration was measured through one growing season from the beginning of June to the end of August, 2016. Date of measurement was used as a proxy to show the water deficit that occurs as increased summer heat dries the soil (Figure 15). Water Use Efficiency (WUE), which is a measure of the amount of water used to photosynthesize carbon, was calculated by dividing net photosynthesis (A_N) by Transpiration (E) (A_N/E).

Pan evapotranspiration rate, average temperature, and precipitation for the growing period from June through August was obtained from a weather station located in the campus botanic garden (Figure 16).[57] Within each species, groups were compared by planting type—pit, strip or park—and date of measurement using a general linear model calculated with Minitab software.[58] The threshold for significant difference was below p=0.05.

To understand whole tree and shrub water use, leaf measurements were scaled up by calculating canopy volume and leaf area. Height of tree was measured using a Suunto clinometer to the nearest 0.31 meter (1 ft) while standing at a distance of 10 to 20 meters (32.8-65.6 feet), depending on the available distance from the tree. Average diameter of the trunk of the tree was measured at 1.37 meters (4.5 ft) above the ground using a diameter tape. Multiple trunked trees—two of the maples—were calculated by adding the individual trunk diameters squared and then finding the square root of this sum. Canopy

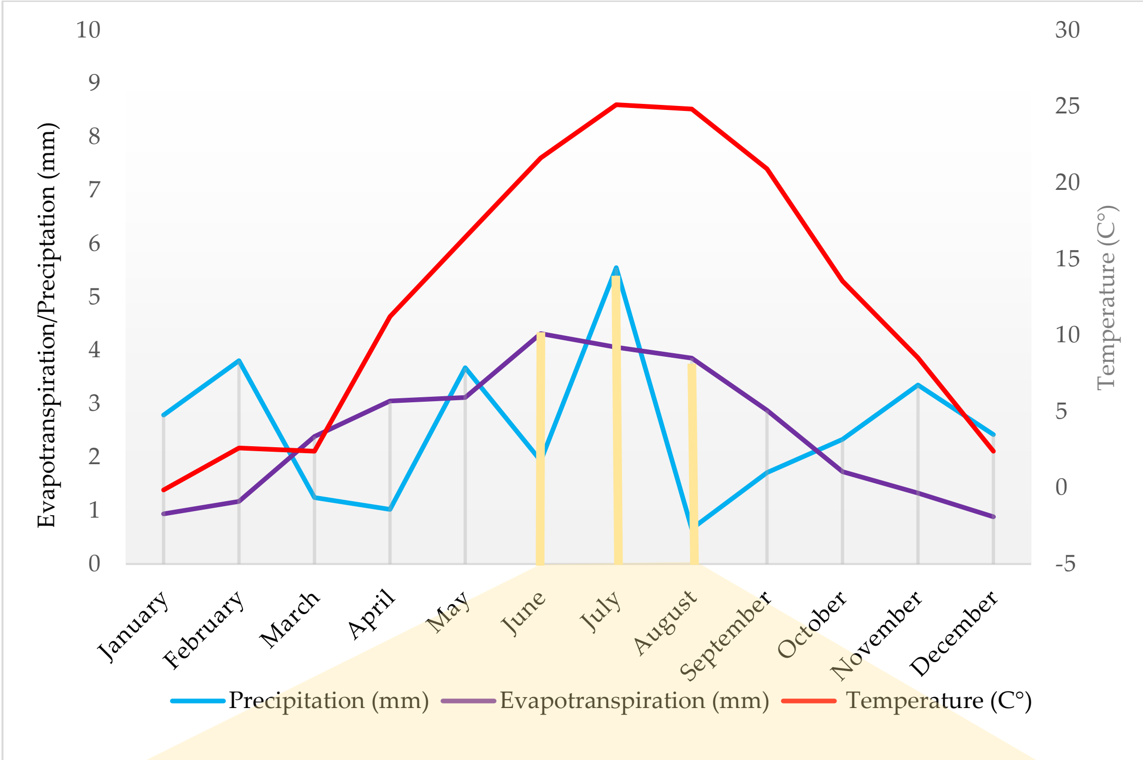


Figure 15: Average Monthly Weather Data. New Brunswick, NJ

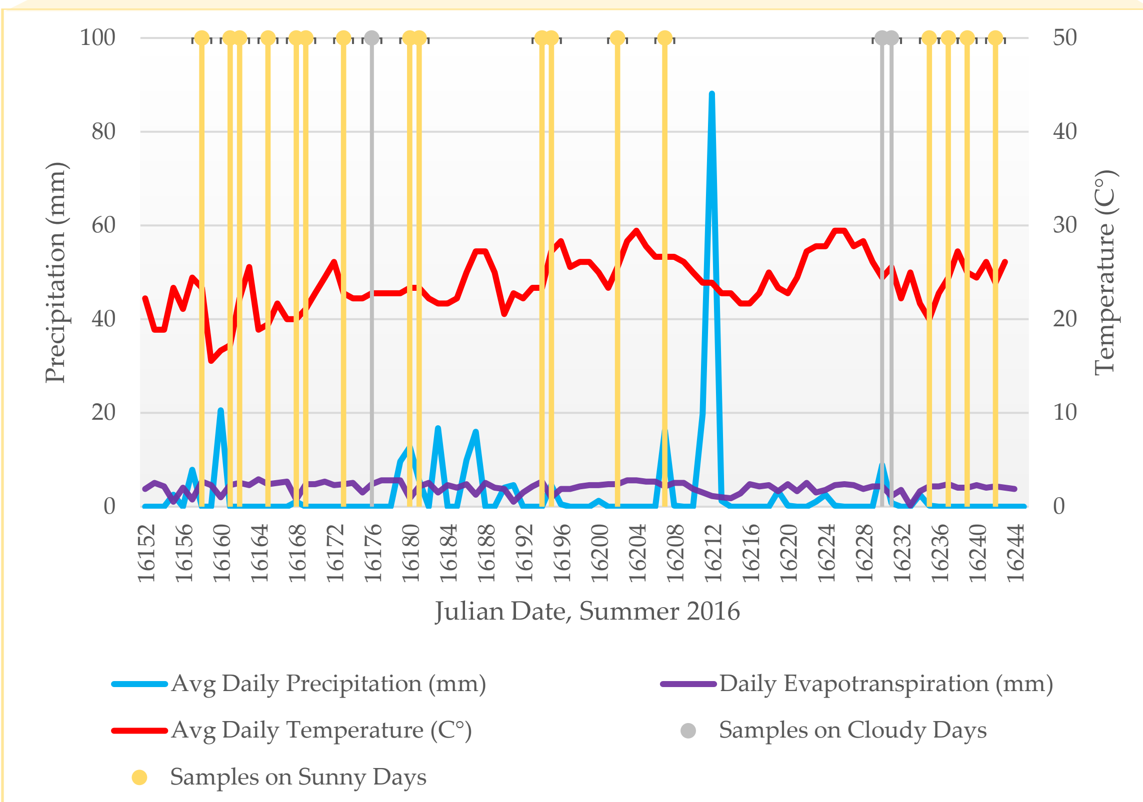


Figure 16: Daily evapotranspiration, precipitation and average temperature for the period of study, New Brunswick, NJ.

radius was measured using a meter tape from trunk center to branch tip at the four cardinal directions and converted to diameter by averaging the north-south and east-west dimensions.

Crown projection was calculated from the canopy diameter squared x a constant of 0.785. Total water use was extrapolated from these measurements using Lindsey and Bassuk's formula:[59]

Daily tree water use=LSA x T_s

where:
LSA=Leaf Surface Area
T_s=Total transpiration

Leaf Surface Area was measured using Lindsey and Bassuk's photographic analysis technique.[60] Trees photographs were scaled from a known measurement in AutoCAD (AutoCAD, 2013), then using Photoshop (Adobe Photoshop CC, 2016), a ratio of foliage pixels to standard frame area was derived and used to calculate surface leaf area.

Shrub volume measurements were calculated using the derived canopy formula.[61]

$CV=2/3\pi H(A/2xB/2)$

where:
H = height
A and B= diameter at 50% height at right angles.

Height was measured from the ground to the apex of the shrub using a meter tape. Diameter was taken at cardinal points from the center of the shrub using a pole through the plant at 50% height to the nearest centimeter.

Scaling from leaf to canopy was calculated by averaging transpiration measurements and converting to kg m^{-2} s^{-1}, then scaling by multiplying by leaf surface area to arrive at total liters day^{-1}. [62] This method suffers from a lack of precision by not taking the variations in wind speeds, leaf temperatures, vapor pressures, and radiation levels in the canopy into account, but is meant to illustrate the impact of decreased leaf surface area on a tree's ability to transpire.[63]

Planting treatments were measured and assigned to a type based on root constriction. When trees shared a planting pit, the total pit area was divided by the number of trees in the pit to determine planting zone. This method of pit selection, used only for *Acer rubrum*, may have reduced the divergence in transpiration measurements in parking lot trees. Trees do share root space and resources in smaller growing locations.[64]

Measurements were recorded and analyzed in an Excel spreadsheet by species.

Chapter 3: Results

Parking lots ranged in size from 0.2 ha (0.5 acres) to a 10 ha (27 acre) series of lots. Planting pits ranged from 3.24 m^2 (35 ft^2) to 20 m^2 (215 ft^2) in area, while the strips ranged from 57 (613 ft^2) to 225 m^2 (2421 ft^2) (Table 1). Trees ranged in size with park like trees generally bigger and healthier than trees in parking lots (Table 2, Figure 17, Figure 18). Shrubs tended to be of equal size and health compared to those in parking lots (Table 3, Figure 19).

Leaf scale transpiration rates for both trees and shrubs were compared between planting treatments and day of measurements. Comparisons were developed with a general linear model. Date of measurement was predictably

Species	Total specimens/ species	Range of Bed Area in m^2			Number of measurement days/total samples
		Pit	Strip	Park	
Trees:		3	3	3	
Acer rubrum	9	25-28.75	57-81		7/189
Gleditsia triacanthos	9	5.4	16-53.3		6/162
Zelkova serrata	9	3.25-20	76.4-225		7/189
Shrubs		3		3	
Euonymous alatus 'Compactus'	6	2.25			5/73
Ilex glabra	6	1.21			6/108
Rosa rugosa	6	1.35-1.5			6/108
Spirea japonica 'Gold Mound'	6	1.21			7/126

Table 1: Table showing Genus species, number of replicates, area of growing space, and number of measurements.

Tree and number of specimens	Bed	Diameter of trunk (cm)	Diameter of crown (m²)	Height (m)	Health Index Score
Acer rubrum					
3	Park	5.5-23.1	2.0-6.0	4.8-15.0	Healthy/Fair
3	Strip	9.0-10.2	2.8-4.0	6.0-9.0	Poor/Critical
3	Pit	5.2-8.2	2.0-2.5	3.5-8.0	Fair/Poor
Gleditisia triacanthos					
3	Park	12.3-17.0	4.0-7.0	8.23-14.0	Healthy/Fair/ Poor
3	Strip	10.6-12.5	3.2-5.1	3.8-6.8	Poor/Critical
3	Pit	8.2-11.0	1.9-3.5	2.5-4.8	Poor/Critical
Zelkova serrata					
3	Park	13.8-22.0	4.3-7.8	10.0-12.00	Healthy/Fair
3	Strip	10.0-16.2	3.7-5.3	7.5-12.0	Healthy/Fair/ Poor
3	Pit	8.6-10.4	1.0-3.0	4.0-7.5	Fair/Poor/Cri tical

Table 2: Trees and range of measurements for trunk diameter, canopy diameter, height, health and sample number

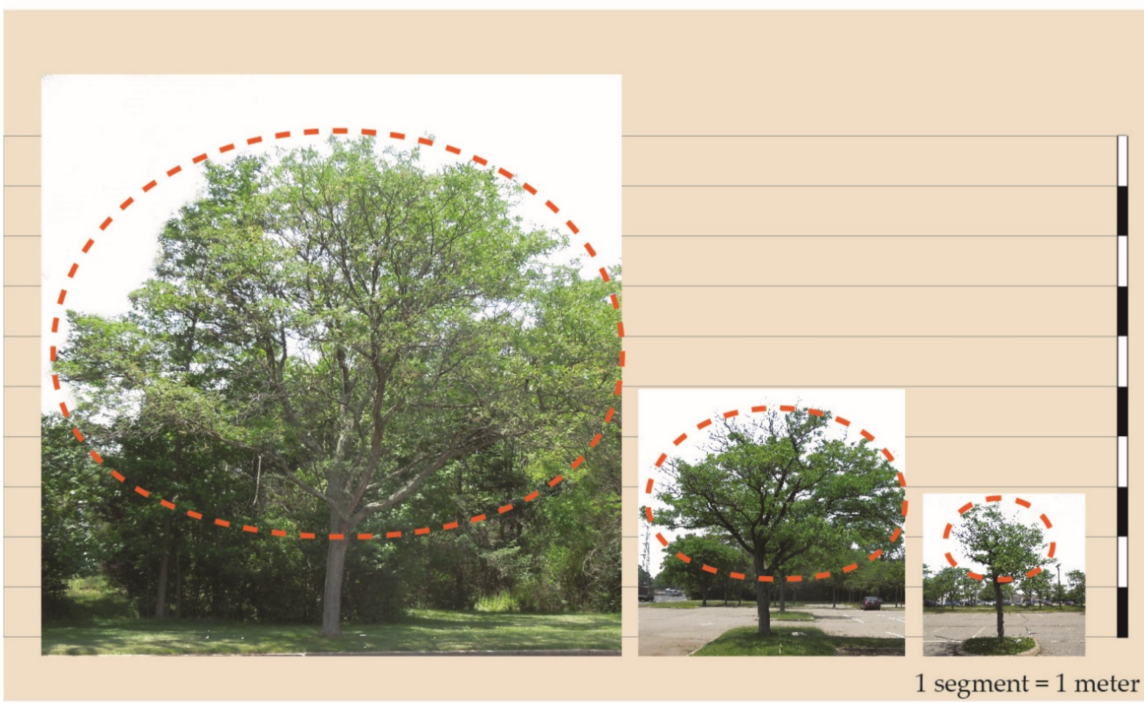


Figure 17: Trees from pits and strips in parking lots were generally much smaller and in poorer health than those in park-like settings. Here *Gleditsia triacanthos* in the same location and the same age, grew much larger with unrestricted root grown on the left compared to same age trees in strips, center, and pits, right.

Figure 18: Though the trees in pits and strips were smaller than those in park-like settings, I chose the healthiest of the trees of the same age and location in the parking lots. Here, *Zelkovas* on the right and left were selected for the study, while the tree in the center was obviously unhealthy and not selected for the study. The unhealthy tree ultimately died late in the summer.

Shrubs	Bed	Canopy	Height	Health
Euonymous alatus 'Compactus'				
3	lot	1.3-1.6	1.2	Healthy
3	park	1.7-2	1.6	Fair
Ilex glabra				
3	lot	1.8-3.0	1.4	Fair/Poor
3	park	0.1-6.1	1.8	Healthy/Fair
Rosa rugosa				
3	lot	0.1-1.6	1	Fair
3	park	0.4-1.0	1.8	Poor
Spirea japonica 'Gold Mound'				
3	lot	0.20	0.6	Healthy /Fair
3	Park	0.4-0.6	0.8	Healthy

Table 3: Shrubs and measurements for canopy diameter, height, type of treatment, and Health Index score

Figure 19: Shrubs from park-like settings and parking lots were of similar size and health regardless of age. Here *Ilex glabra* from a parking lot on the left and at Rutgers Gardens on the right.

significant (p-value=0.000-0.001) for all species as the gradual drying of soil as heat increased decreased the amount of transpiration. Planting treatment was significant for no tree and 3 out of 4 species of shrubs—*Euonymous alatus*, *Ilex glabra*, and *Rosa rugosa* (p-value=0.000-0.006) (Table 4-Table 10). Because there were only 2 treatments for shrubs, no further confidence testing was needed.

There were several points where the plant response data shifted abruptly from one observation to the next. These shifts tended to occur after rain, on cloudy days, and due to differences in timing of measurements, placement of plants, or maintenance considerations. For example, measurements of *Rosa rugosa* were affected by combinations of these factors that may have skewed measurements: During Measurement 5, on August 18th, at 8:30 to 8:45 in the morning in the parking lot, leaf temperature averaged 26 °C (79 °F) and transpiration ranged between 1.74 mmol H_2O m^{-2} s^{-1} to 5.88 mmol H_2O m^{-2} s^{-1}. Four hours later in the park, leaf temperature averaged 30 °C (86 °F) and transpiration ranged from 0.54 mmol H_2O m^{-2} $s^{-1}$to 2.24 mmol H_2O m^{-2} s^{-1}. In the park like setting, weedy vines had begun to grow over the plants as the season progressed, while in the parking lot, the shrubs were pruned severely in the latter half of the summer, beginning with the measurements on August 18^{th}. Additionally, while not directly irrigated in the parking lot, the shrubs that were measured were near an irrigated planting bed that splashed water onto the ground. Water potentially seeped into the ground through a crack between the asphalt and concrete curb and provided an additional water source for the plants in parking lots. The effect of leaf temperature and time of day likely influenced transpiration rates, but significant differences could have happened from irrigation, pruning, which has been shown to increase transpiration per unit area,[65] or leaf shading from the vines may have had an effect on the transpiration rate.

Acer rubrum

Health of trees ranged from Critical to Healthy, with trees in pits rating as Critical/Poor and strips, Poor/Fair compared to the Fair/Healthy scores for trees in park like settings. Transpiration ranged in value from 0.12 mmol H_2O m^{-2} s^{-1} to 4.73 mmol H_2O m^{-2} s^{-1}, with a mean of 1.43 mmol H_2O m^{-2} s^{-1} (Figure 20). Transpiration measurements tended to be lower across all treatments with a median of 1.28 mmol H_2O m^{-2} s^{-1}. Leaf scale WUE ranged from 1.5 to 10.5 μmol CO_2/mmol H_2O with a mean of 4.86 μmol CO_2/mmol H_2O and a median of 4.64 μmol CO_2/mmol H_2O (Figure 21).

Comparing these trees by treatment had a p-value of 0.057, below our established criterion for significant difference at α=0.05 (Table 4). Transpiration measurements had wide variations in individual trees, and the maximum number of measurements flagged as outliers in preliminary statistics. For example, one tree, AR9, had a wide range in transpiration across the 7/25 measurement from 4.73 mmol H_2O m^{-2} s^{-1} to 0.33 mmol H_2O m^{-2} s^{-1}. On 8/26,

Acer rubrum					
Factor	Type	Levels	Values		
Treatment	Fixed	3	1, 2, 3		
Date	Fixed	14	16158, 16161, 16165, 16173, 16176, 16180, 16181, 16194, 16195, 16202, 16207, 16230, 16239, 16242		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	4.067	2.0334	2.92	0.057
Date	13	25.375	1.9519	2.80	0.001
Error	167	116.405	0.6970		
Lack-of-Fit	13	8.280	0.6369	0.91	0.547
Pure Error	154	108.125	0.7021		
Total	182	147.012			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
0.834886	20.82%	71%			

Table 4: General Linear Model Results, *Acer rubrum*

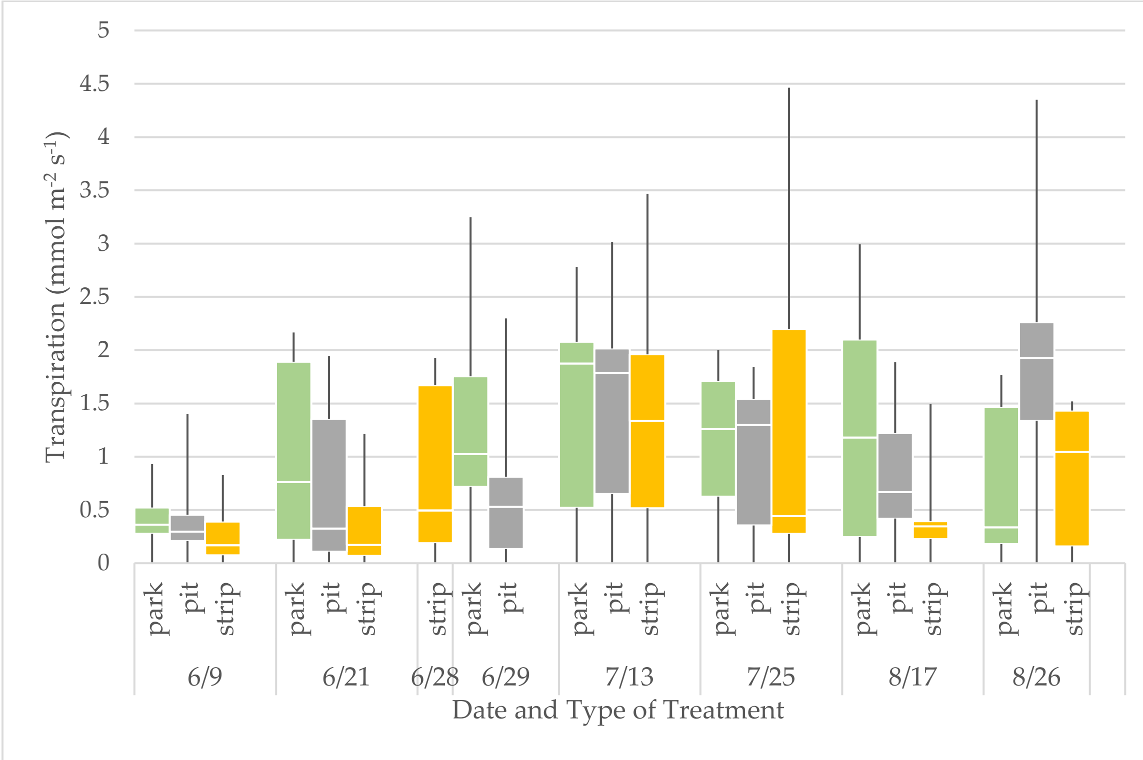


Figure 20: Transpiration measurement distribution by measurement day and treatment, *Acer rubrum*

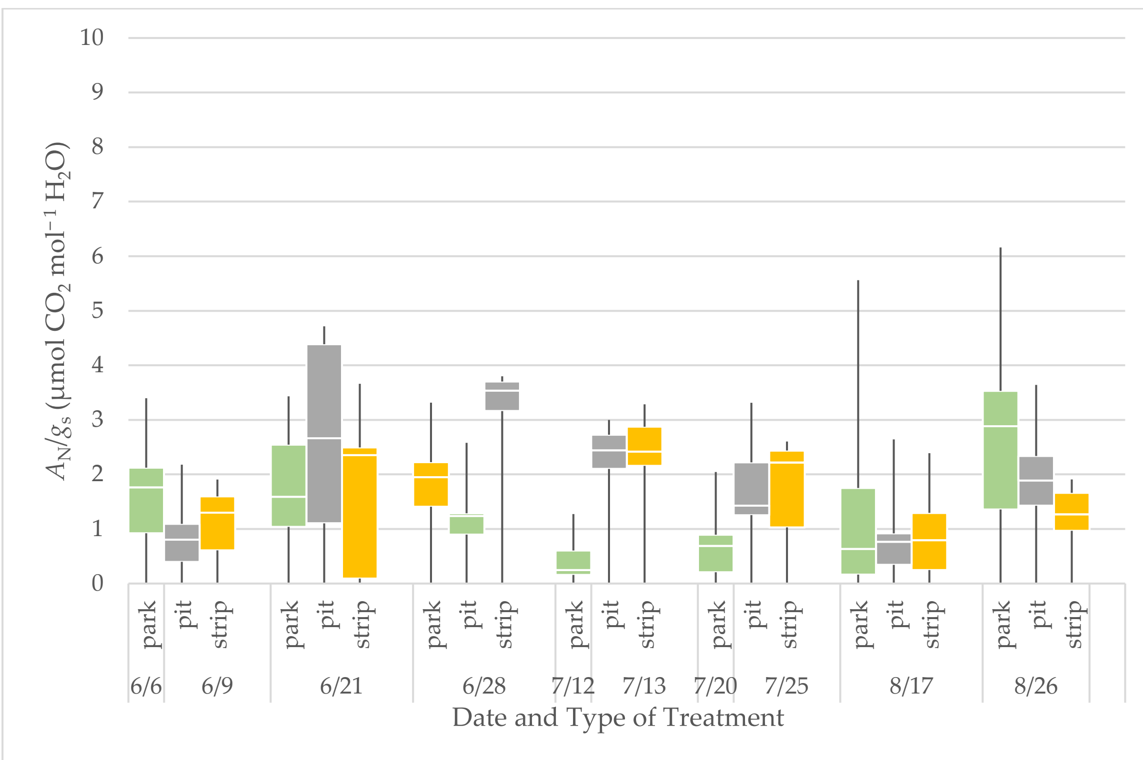


Figure 21: Water Use Efficiency by measurement day and type of treatment, *Acer rubrum*

another tree, AR3, had a similar wide range of values, ranging from 1.84 mmol H_2O m^{-2} s^{-1} to 4.64 mmol H_2O m^{-2} s^{-1}. Sampling errors such as testing leaves from different heights in the trees and non-response of *A. rubrum* to sampling after excising likely caused some of this differing measurements, unrelated to treatment or day of measurement.

Gleditsia triacanothos var. inermis

Trees ranged in health from Critical to Healthy on the Health Index scale. Trees in strips and pits ranked as Critical or Poor, while trees in parks ranked Poor, Fair, and Healthy. This species had the widest range of transpiration values: 0.31 mmol H_2O m^{-2} s^{-1} to 7.30 mmol H_2O m^{-2} s^{-1} with a mean of 3.471 mmol H_2O m^{-2} s^{-1} and a similar median of 3.465 mmol H_2O m^{-2} s^{-1} (Figure 22). Leaf scale WUE ranged from 2.12 to 12.83 μmol CO_2/mmol H_2O with a mean of 4.76 μmol CO_2/mmol H_2O and a median of 4.60 μmol CO_2/mmol H_2O (Figure 23).

The planting site treatment effect was not deemed significant at p=0.092 (Table 5). *Gleditisia* is known to be a drought tolerant tree capable withstanding high temperatures[66] which may explain the ability at the leaf scale to move large amounts of water when available, though average water use efficiency was similar *A. rubrum.*

Additionally, spaces between measurement days may have influenced comparison of measurements. A large rain on 6/8 may have increased

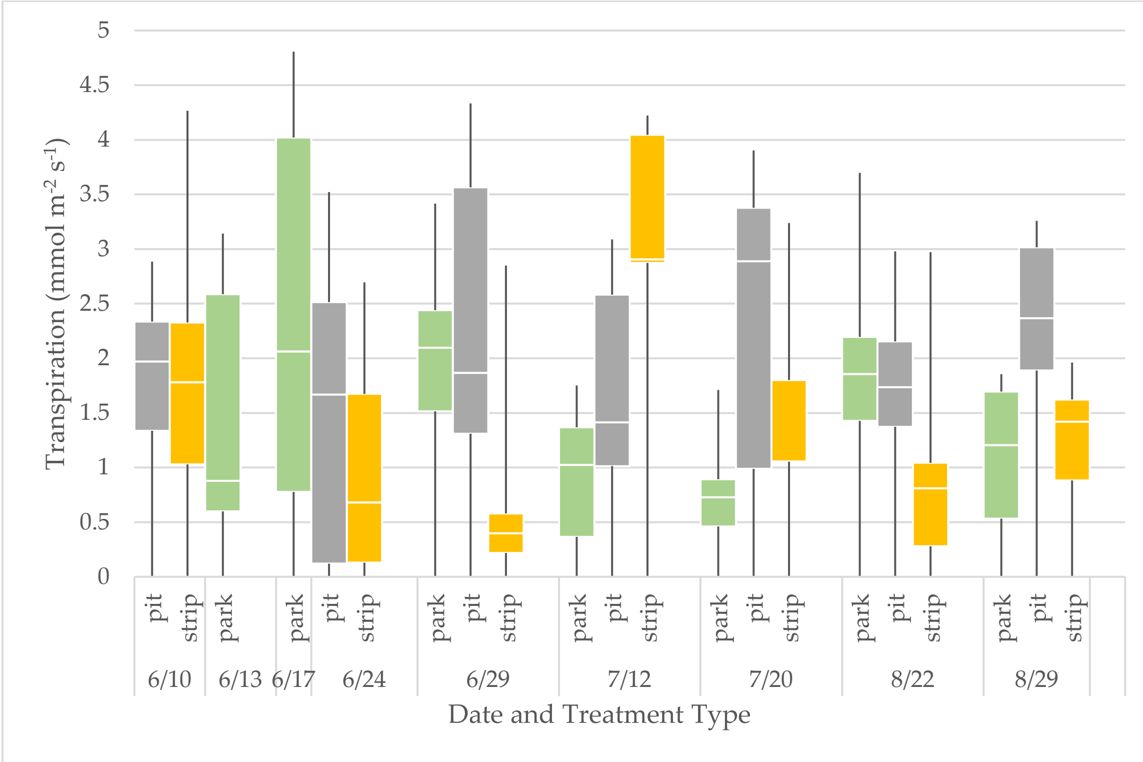


Figure 22: Transpiration measurement distribution by measurement day and treatment, *Gleditsia tracanthos*

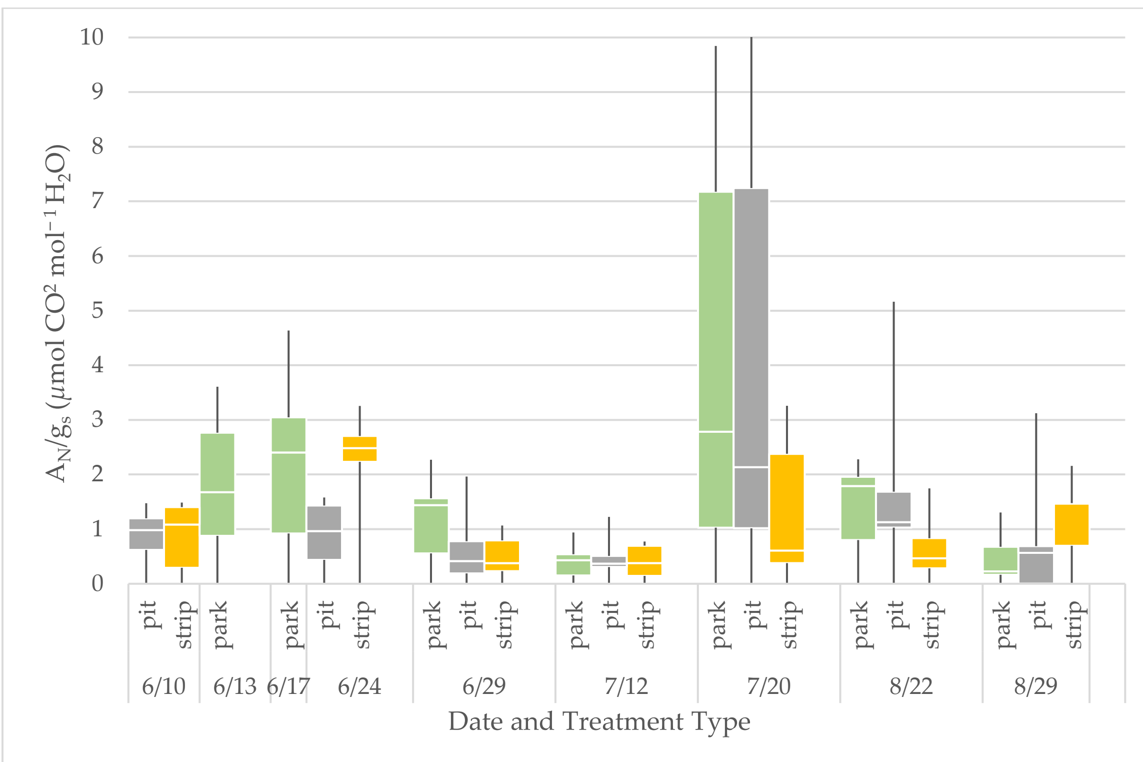


Figure 23: Water Use Efficiency by measurement day and type of treatment, *Gleditsia tracanthos*

transpiration on 6/10 in pit and strip trees, but the available water in the soil may have decreased by 6/13 when 2 out of 3 park trees were measured. Similarly a partly cloudy day on 6/24 may have decreased transpiration in the pits and strips for Measurement 2, but the relatively sunny day following some rainfall on 6/17 showed higher transpiration in park trees. A rainy period between 6/27-29 may have influenced water movement during Measurement 3.

Gleditsia triacanthos v. inermis					
Factor	Type	Levels	Values		
Treatment	Fixed	3	1, 2, 3		
Date	Fixed	15	16158, 16162, 16165, 16169, 16173, 16176, 16180, 16181, 16194, 16195, 16202, 16230, 16235, 16239, 16242		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	6.088	3.044	2.42	0.092
Date	14	257.529	18.395	14.62	0.000
Error	172	216.472	1.259		
Lack-of-Fit	11	35.719	3.247	2.89	0.002
Pure Error	161	180.753	1.123		
Total	188	475.978			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
1.12186	54.52%	50.29%	46.41%		

Table 5: General Linear Model Results, *Gleditsia triacanthos v. inermis*

Zelkova serrata

Plants ranged in health from Critical to Healthy. Again, trees in parks had the best health overall, rating Fair to Healthy, while trees in pits and strips ranked from Critical to Fair with the exception of one Healthy tree that had a large planting bed. Transpiration ranged from 0.07 mmol H_2O m^{-2} s^{-1} to 4.64 mmol H_2O m^{-2} s^{-1}, with a mean of 1.50 mmol H_2O m^{-2} s^{-1} (Figure 24). Like *A.*

rubrum, the median was lower at 1.22 mmol H_2O m^{-2} s^{-1}, and there was little correlation between the variables (p-value=0.429) (Table 6). Rain and cloudy days affected measurements as with the other trees. Leaf scale WUE ranged from 1.77 to 17.58 μmol CO_2/mmol H_2O with a mean of 4.62 μmol CO_2/mmol H_2O and a median of 4.51 μmol CO_2/mmol H_2O (Figure 25).

Tree transpiration was less correlated to planting treatment and date of measurement than shrubs, although there was variation here as well.

Zelkova serrata					
Factor	Type	Levels	Values		
Treatment	Fixed	3	1, 2, 3		
Date	Fixed	13	16158, 16161, 16173, 16176, 16180, 16181, 16194, 16195, 16202, 16207, 16230, 16239		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	1.463	0.7315	0.85	0.429
Date	11	46.843	4.2585	4.95	0.000
Error	172	147.880	0.8598		
Lack-of-Fit	15	19.820	1.3213	1.62	0.074
Pure Error	157	128.060	0.8157		
Total	185	197.671			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
0.927238	25.19%	19.53%	12.96%		

Table 6: General Linear Model Results, *Zelkova serrata*

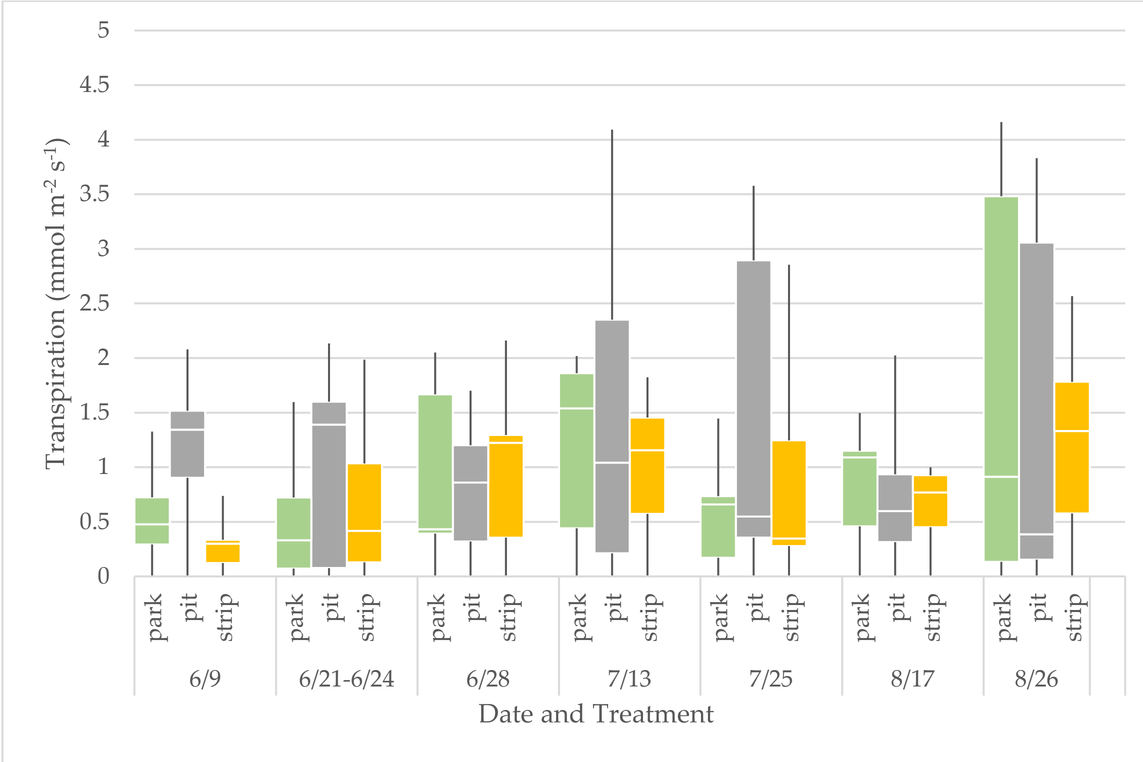


Figure 24: Transpiration measurement distribution by measurement day and treatment, *Zelkova serrata*

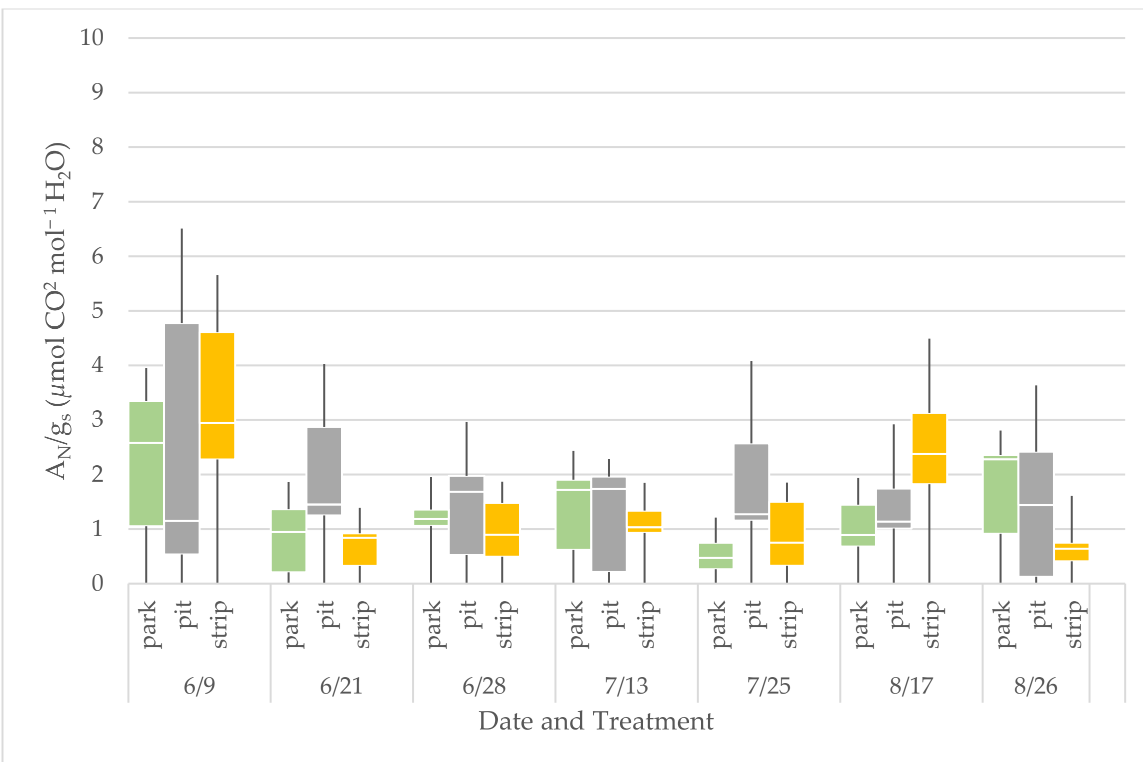


Figure 25: Water Use Efficiency by measurement day and type of treatment, *Zelkova serrata*

Euonymous alatus 'Compactus'

Plants in parking lots rated as Healthy, while those in park settings rated as Fair due to lower opacity ratings. This species had the narrowest range of transpiration across all species—0.06 mmol H_2O m^{-2} s^{-1} to 3.13 mmol H_2O m^{-2} s^{-1}, with a mean of 1.06 mmol H_2O m^{-2} s^{-1} and a slightly lower median of 0.97 mmol H_2O m^{-2} s^{-1} (Figure 26). Leaf scale WUE ranged from 1.32 to 12.73 µmol CO_2/mmol H_2O with a mean of 5.36 µmol CO_2/mmol H_2O and a median of 5.29 µmol CO_2/mmol H_2O (Figure 27). The correlation of the mean measurements to planting treatment was significant with a p-value of 0.000 (Table 7). Shrubs in the park like setting transpired more than the parking lot specimens.

Euonymous alatus 'Compactus'					
Factor	Type	Levels	Values		
Treatment	Fixed	2	2, 3		
Date	Fixed	6	16176, 16180, 16181, 16195, 16231, 16237		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	1	6.029	6.0289	30.27	0.000
Date	5	13.790	2.7580	13.85	0.000
Error	67	13.343	0.1991		
Lack-of-Fit	3	2.877	0.9591	5.87	0.001
Pure Error	64	10.465	0.1635		
Total	73	33.351			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
0.446258	59.99%	56.41%	47.97%		

Table 7: General Linear Model Results, *Euonymous alatus* 'Compactus

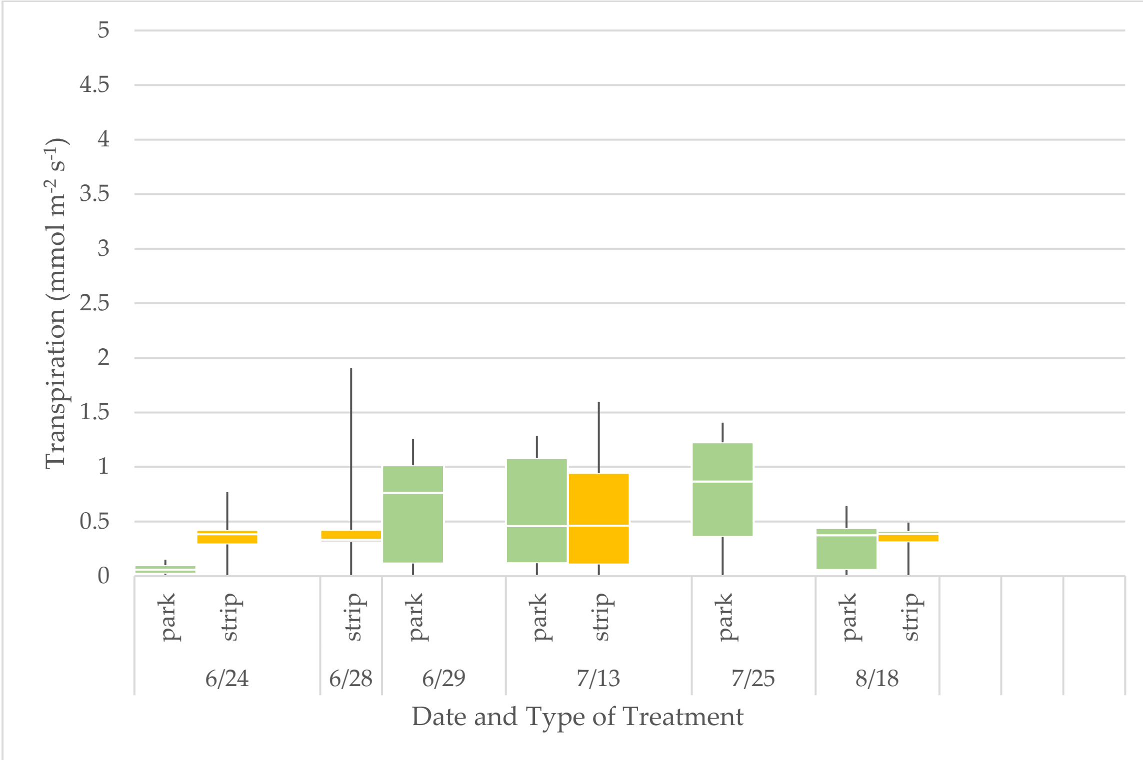


Figure 26: Transpiration measurement distribution by measurement day and treatment, *Euonymous alatus* 'Compactus'

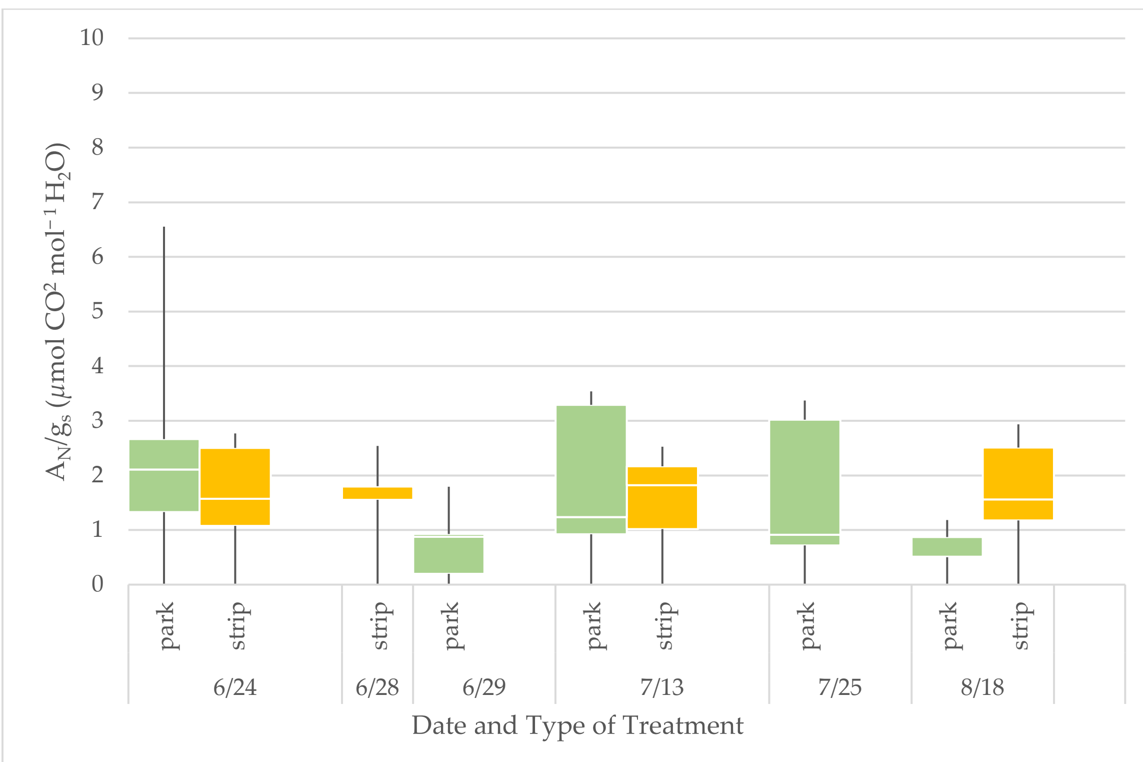


Figure 27: Water Use Efficiency by measurement day and type of treatment, *Euonymous alatus* 'Compactus'

Ilex glabra

Shrubs in parking lots rated in Poor to Fair health compared to Fair to Healthy in park settings. Parking lot shrubs had less opacity and more dieback than shrubs in parks. These shrubs transpired 0.12 mmol H_2O m^{-2} s^{-1} to 4.72 mmol H_2O m^{-2} s^{-1}, with a mean of 1.73 mmol H_2O m^{-2} s^{-1} and a lower median of 1.51 mmol H_2O m^{-2} s^{-1} (Figure 28). Leaf scale WUE ranged from 2.01 to 40.74 μmol CO_2/mmol H_2O with a mean of 6.56 μmol CO_2/mmol H_2O and a median of 5.45 μmol CO_2/mmol H_2O (Figure 29). This species had a significant relationship between the variables of the statistical model with a p-value of 0.000 (Table 8). The plants in the park were able to transpire more water following rain, than their parking lot counterparts. *Ilex glabra* is the sole evergreen species of the

Ilex glabra					
Factor	Type	Levels	Values		
Treatment	Fixed	2	2, 3		
Date	Fixed	9	16162, 16165, 16169, 16176, 16181, 16194, 16202, 16235, 16242		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	1	98.431	98.4306	219.99	0.000
Date	8	21.398	2.6747	5.98	0.000
Error	115	51.455	0.4474		
Lack-of-Fit	4	2.610	0.6526	1.48	0.212
Pure Error	111	48.844	0.4400		
Total	124	197.981			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
0.668904	74.01%	71.98%	69.13%		

Table 8: General Linear Model Results, *Ilex glabra*

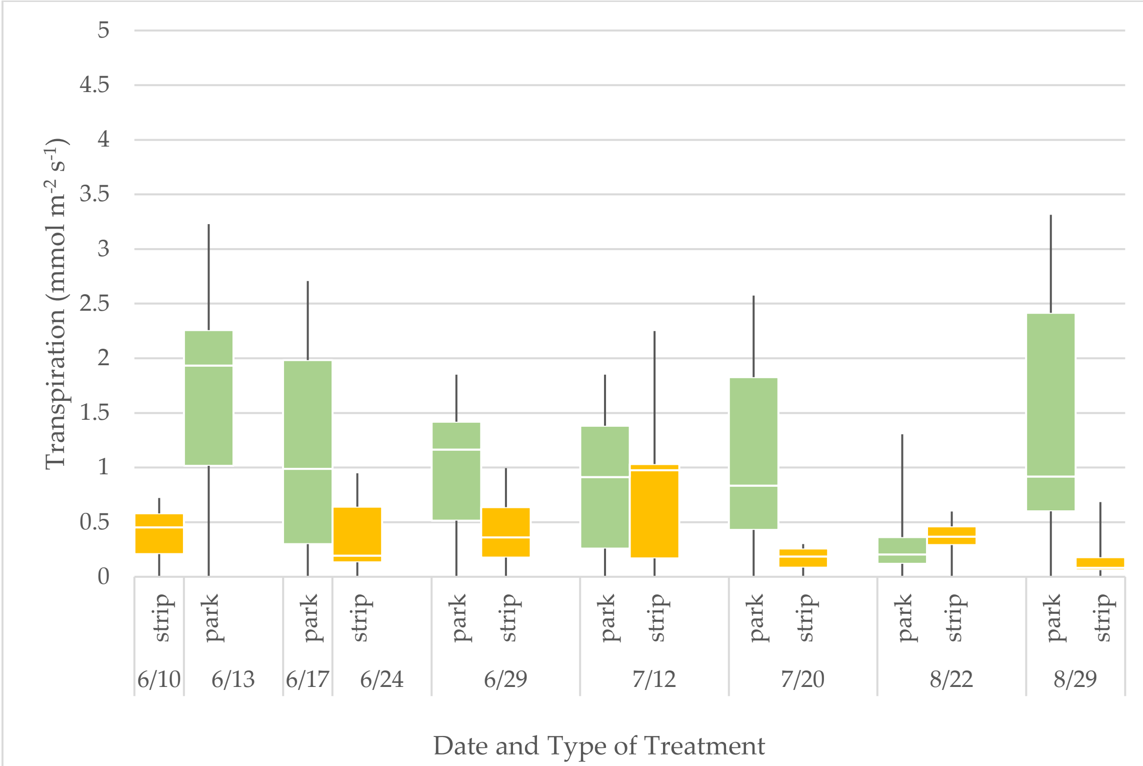


Figure 28: Transpiration measurement distribution by measurement day and treatment, *Ilex glabra*

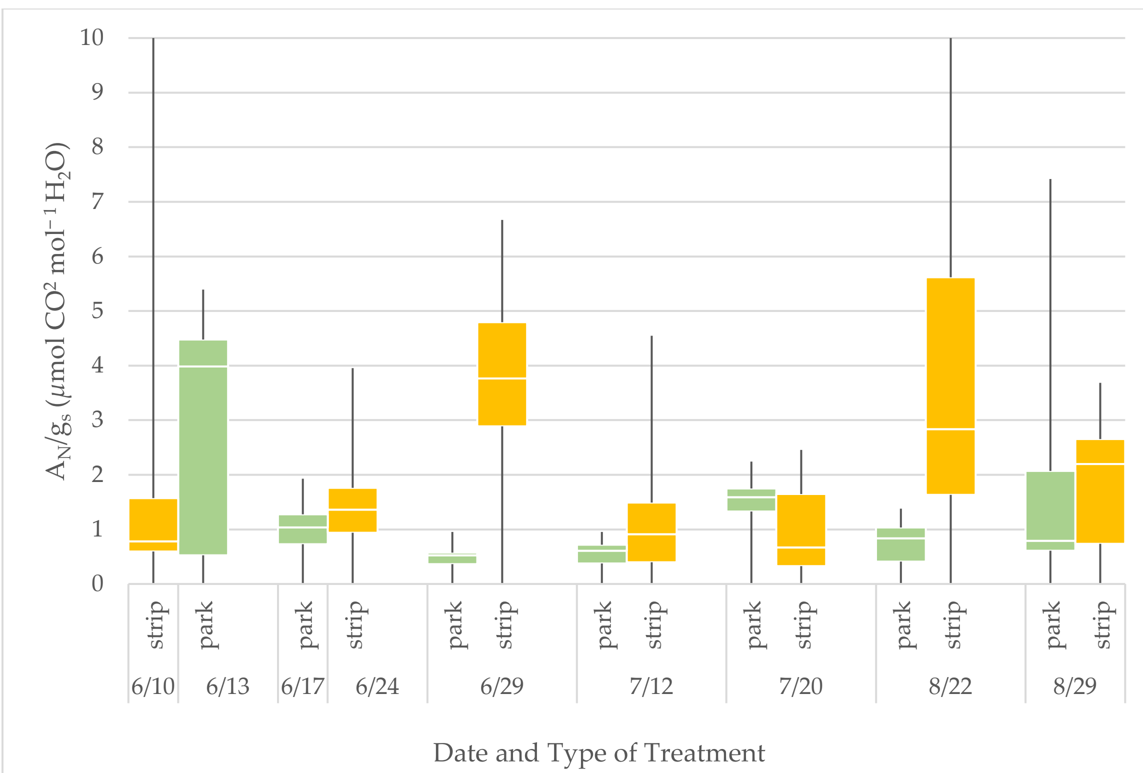


Figure 29: Water Use Efficiency by measurement day and type of treatment, *Ilex glabra*

group and tends to have leaves that can withstand more water stress.[67] *I. glabra* seems to have more tolerance for drought and greater water use efficiency than the other species tested, though their health may suffer with less access to water.

Rosa rugosa

Parking lot plants had Fair health compared to those in the park like settings, which rated Poor. Shrubs in parks had less opacity and more twig dieback than parking lot plants. Transpiration for this species ranged from 0.26 mmol H_2O m^{-2} s^{-1} to 5.88 mmol H_2O m^{-2} s^{-1} with a mean of 2.74 mmol H_2O m^{-2} s^{-1} and a similar median of 2.62 mmol H_2O m^{-2} s^{-1} (Figure 30). Leaf scale WUE ranged from 2.24 to 11.95 μmol CO_2/mmol H_2O with a mean of 4.56 μmol CO_2/mmol H_2O and a median of 4.24 μmol CO_2/mmol H_2O (Figure 31). *R. rugosa* was also correlated with the statistical model with a p-value of 0.006 (Table 9),

Rosa rugosa					
Factor	Type	Levels	Values		
Treatment	Fixed	2	2, 3		
Date	Fixed	10	16158, 16165, 16169, 16180, 16181, 16194, 16195, 16231, 16237, 16242		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	1	8.328	8.3284	7.79	0.006
Date	9	51.776	5.7529	5.38	0.000
Error	96	102.579	1.0685		
Lack-of-Fit	1	15.623	15.6229	17.07	0.000
Pure Error	95	86.956	0.9153		
Total	106	157.898			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
1.03370	35.03%	28.27%	20.00%		

Table 9: General Linear Model Results, *Rosa rugosa*

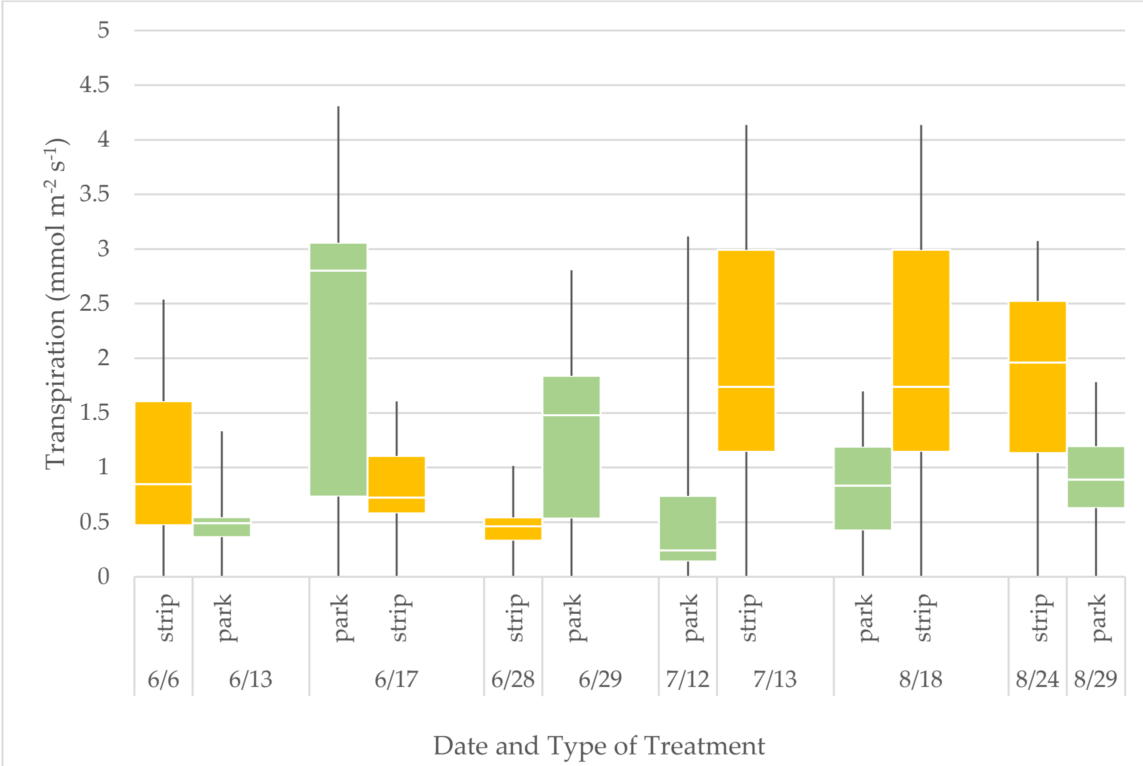


Figure 30: Transpiration measurement distribution by measurement day and treatment, *Rosa rugosa*

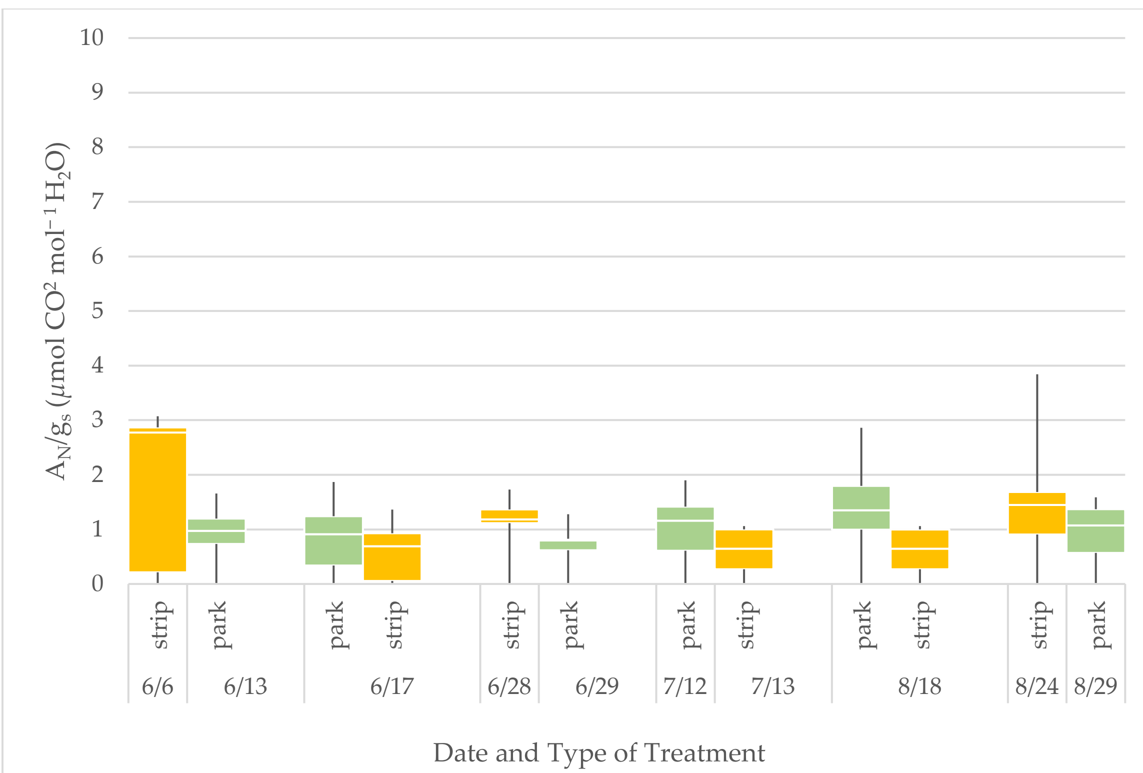


Figure 31: Water Use Efficiency by measurement day and type of treatment, *Rosa rugosa*

though the model found more transpiration in parking lot plants, rather than shrubs in the park setting. This twist may have been due to the aforementioned day and time of treatment, maintenance techniques and adjacent irrigation.

Spiraea japonica

All Spiraea rated as Healthy except one parking lot shrub which rated as Fair, due to some twig dieback and reduction in opacity. Water movement through the plant ranged from 0.11 mmol H_2O m^{-2} s^{-1} to 4.88 mmol H_2O m^{-2} s^{-1} with a closely matched mean and median of 2.06 mmol H2O m^{-2} s^{-1} and 2.023 mmol H_2O m^{-2} s^{-1}, respectively (Figure 32). Leaf scale WUE ranged from 0.30 to 13.31 μmol CO_2/mmol H_2O with a mean of 3.89 μmol CO_2/mmol H_2O and a median of 3.55 μmol CO_2/mmol H_2O (Figure 33). Transpiration was not significantly correlated with treatment with a p-value of 0.331 (Table 10). Anomalies resulted from differences in days of measurement and rainfall. On June 17th, a cooler day (average daily temperature of 21 °C or 68 °F) following a slight (1 mm or 0.04 inch) rain after a 7 day drought corresponds to higher transpiration in parking lot shrubs compared to the June 21st measurement of the shrub in the park after 5 days of warmer weather (average daily temperature of 26° C or 79 °F) and only the 1mm rain for the past 13 days.

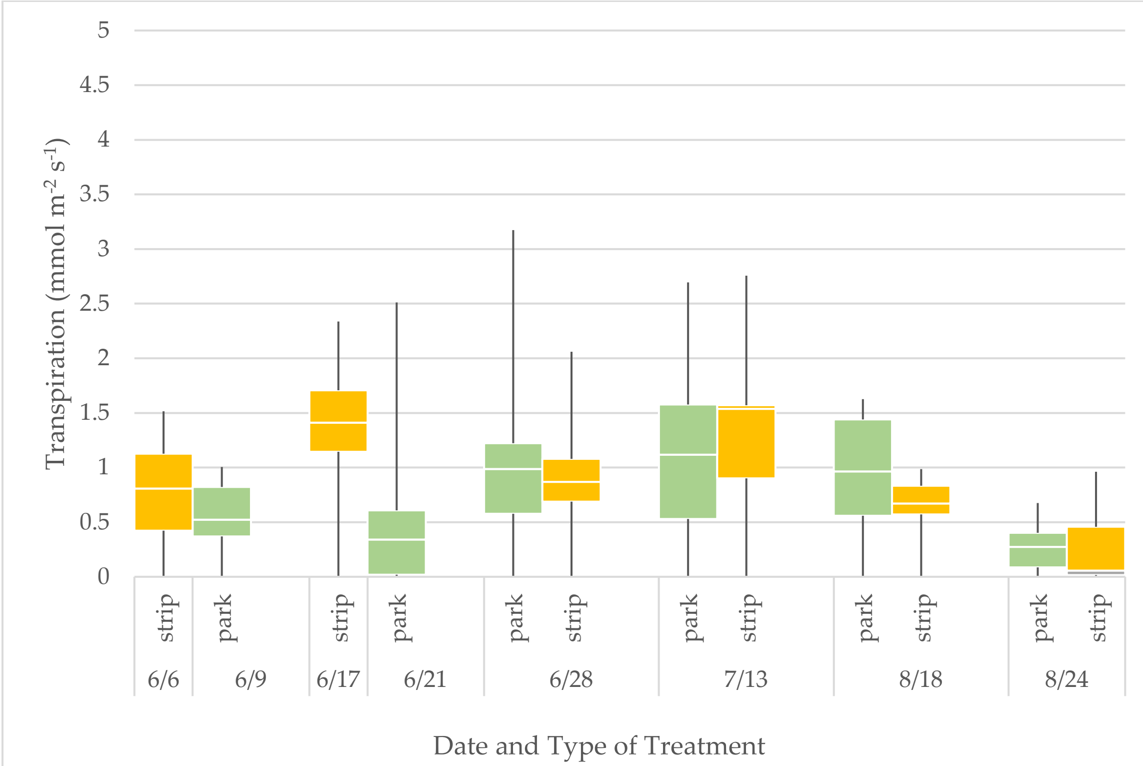


Figure 32: Transpiration measurement distribution by measurement day and treatment, *Spiraea japonica*

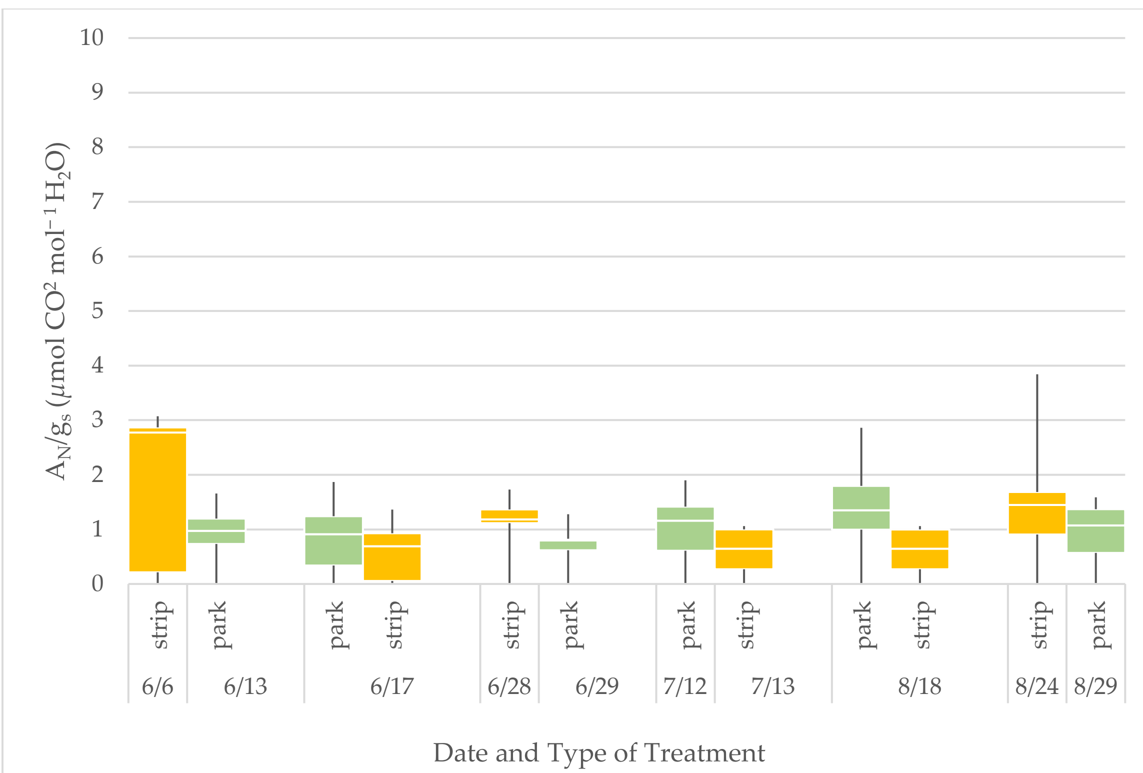


Figure 33: Water Use Efficiency by measurement day and type of treatment, *Spiraea japonica*

Spiraea japonica					
Factor	Type	Levels	Values		
Treatment	Fixed	2	2, 3		
Date	Fixed	8	16158, 16161, 16169, 16173, 16180, 16195, 16231, 16237		
Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	1	0.414	0.4142	0.95	0.331
Date	7	92.270	13.1815	30.39	0.000
Error	99	42.941	0.4337		
Lack-of-Fit	3	0.925	0.3084	0.70	0.552
Pure Error	96	42.016	0.4377		
Total	107	140.956			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred		
0.658595	69.54%	67.07%	63.76%		

Table 10: General Linear Model Results, *Spiraea japonica*

Comparisons

All trees and shrubs transpired during the measurement period. Comparing overall transpiration of trees at the leaf scale, *Zelkova serrata* had the least difference (0.07 mmol H_2O m^{-2} s^{-1} to 4.64 mmol H_2O m^{-2} s^{-1}) with a mean of 1.502 mmol H_2O m^{-2} s^{-1} while *Gleditisa triacanthos* had the most difference (0.31 mmol H_2O m^{-2} s^{-1} to 7.30 mmol H_2O m^{-2} s^{-1}) with a mean of 3.471 mmol H_2O m^{-2} s^{-1}. Shrub transpiration varied. *Euonymous alatus 'Compactus'* was most consistent (0.06 mmol H_2O m^{-2} s^{-1} to 3.13 mmol H_2O m^{-2} s^{-1}) with a mean of 1.06 mmol H_2O m^{-2} s^{-1}, while *Rosa rugosa* varied the most (0.26 mmol H2O m^{-2} s^{-1} to 5.88 mmol H_2O m^{-2} s^{-1}) with a mean of 2.744 mmol H_2O m^{-2} s^{-1}.

Leaf-level WUE varied by species (Figure 21-Figure 33). All trees had similar WUE (4.4-5.1 μmol CO_2/mmol H_2O on average), with *Zelkova* with the most root restriction having the lowest (4.4 μmol CO_2/mmol H_2O) and *Acer* in parks the highest (5.1 μmol CO_2/mmol H_2O). As water availability decreases and atmospheric demand increases as stomata close, WUE should increase due to the steeper gradient for water loss versus carbon gain. As with transpiration, there was little pattern across planting treatments for trees.

Shrubs varied more widely in their WUE (3.7-8.6 μmol CO_2/mmol H_2O on average). Parking lot S*piraea* water use was least efficient (3.7 μmol CO_2/mmol H_2O), while *Ilex* was the most efficient (8.6 μmol CO_2/mmol H_2O)

Scaling to Canopy

As a group, no one species transpired considerably more than another, and thus, using transpiration rates to select parking lot plants is not a reasonable conclusion. Considering transpiration rates at a whole canopy level does have design implications in terms of stormwater capture. Scaling the amount of transpiration from leaf scale to the canopy scale, trees and shrubs with less leaf surface area, regardless of species, are limited in the total amount of water they can transpire (Table 11, Table 12). Trees with unrestricted roots generally had the largest leaf surface area and trees with partial constriction had on average larger surface area than pit trees. Three trees--2 *Gleditisia* and 1 *Zelkova*--growing in pits actually had less surface area than shrubs. Shrubs tended to have similar canopy volumes, except *Ilex* which ranged from 1.0 to 6.1 m^2 in the park compared to parking lot shrubs which averaged 1.9-2.9 m^2. These parking lot shrubs were sheared in late summer, while those in the park were not.

Tree and number of specimens	Bed	Leaf Surface Area (m^2)	Transpiration/day (Estimate) (l)
Acer rubrum			
3	Park	12.5-128.2-	6.7-85
3	Strip	17.0-30.8	7.3-12.6
3	Pit	9.5-20.9	4.0-11.0
Gleditisia triacanthos			
3	Park	26.8-109.7	34.4-158.0
3	Strip	6.7-17.3	8.0-26.0
3	Pit	1.5-10.7	2.2-14.5
Zelkova serrata			
3	Park	62.5-92.2	32.8-62.3
3	Strip	29.2-86	17.3-50.8
3	Pit	4.3-26.9	2.1-12.3

Table 11: Tree Leaf Surface Area and Estimated Whole Canopy Transpiration Rate

Shrubs	Bed	Leaf Surface Area (m^2)	Transpiration/day (Estimate) (l)
Euonymous alatus 'Compactus'			
3	lot	0.2	0.2
3	park	0.4-0.6	0.3
Ilex glabra			
3	lot	1.9-2.9	0.4-1.0
3	park	1.0-6.1	1.1-6.7
Rosa rugosa			
3	lot	0.4-0.9	0.4-1.4
3	park	0.9-1.6	0.9-1.4
Spirea japonica 'Gold Mound'			
3	lot	1.3-1.5	0.5-0.7
3	park	1.6-1.8	0.5

Table 12: Shrub Leaf Surface Area and Estimated Whole Canopy Transpiration Rate

Though these this scaling procedure did not consider transpiration variability in sun versus shade leaves, or wind or humidity differences within the canopy, a rough estimate of canopy transpiration was made for the purpose of illustrating the effect of larger canopy on water relations. These amounts do roughly align with other reports of tree transpiration.[68] Larger canopy size directly translated to higher transpiration at a tree scale. Park trees transpired the most, and pit trees the least. *Gleditisa*, of which 7 out of 9 trees were of the same age and location, provides the most accurate comparison of variation in transpiration between larger and smaller trees. A tree growing at the edge of the parking lot without restricted roots transpired 84.7 l^{-1} d^{-1}. The trees in strips in the lot averaged 15.2 l^{-1} d^{-1}. The trees in pits averaged 3.5 l^{-1} d^{-1} (Figure 34). Shrubs transpired about a liter a day.

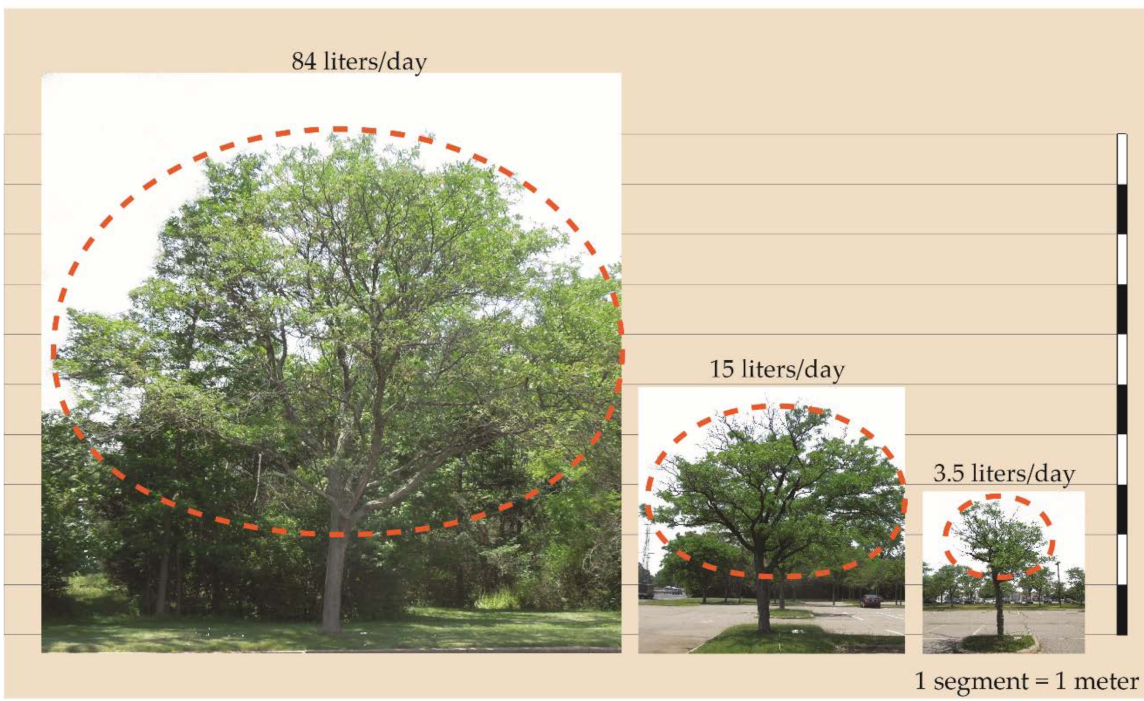


Figure 34: Same age and location Gleditisia triacanthos. Larger trees transpire much more when roots are not restricted by pavement. Shrubs transpired about 1 liter per day.

Chapter 4: Discussion

This study found varying amounts of transpiration in shrubs between parks and parking lots. Two species of shrubs, *Ilex glabra* and *Euonymous alatus* 'Compacta', have higher transpiration in parks rather than parking lot, which had little effect on their health or appearance. *Rosa rugosa* had higher transpiration in the parking lot setting, which was likely caused by day and time of measurement, maintenance issues in the park, and nearby irrigation in the parking lot. *Spiraea* was not affected by planting treatment. While more research needs to be done on individual species, this research can surmise that shrubs can tolerate smaller pit sizes in a parking lot.

A stronger correlation between shrubs and planting treatment as compared to trees could be a result of the better drought tolerance and adaptability by these shrub species. Evergreen leaves, such as *Ilex glabra*, could be better adapted to withstand highs and lows of temperatures, as well as, drought and inundation,[69] while *Euonymous* and *Rosa* are both considered very tolerant species.[70] Shrubs do provide ecological services in a parking lot beyond simple screening. These benefits include stormwater capture, habitat for birds and other wildlife, and as shrubs are often selected for their flowers or fruits, food for wildlife (Figure 35). Furthermore they perform these services while growing in relatively small parking lots pits.

Figure 35: Bee visiting the flower of *Rosa rugosa* at the Costco parking lot, Edison, NJ.

Trees in parking lots, on the other hand, do function on a leaf scale as trees in park like settings. Confirming prior studies concerning trees in restricted growing spaces,[71] trees in small pits and strips in paved environments grow to the size based on the amount of water they receive. A tree may grow to fill the space given, but during drought years, repeated damage to xylem and cells limits the water accessibility to the full height of the tree[72]. These upper reaches of the crown die and are subsequently pruned out (Figure 36).

Considered at a whole tree scale, the greater number of leaves and, subsequently the greater leaf surface area, found on mature trees given adequate

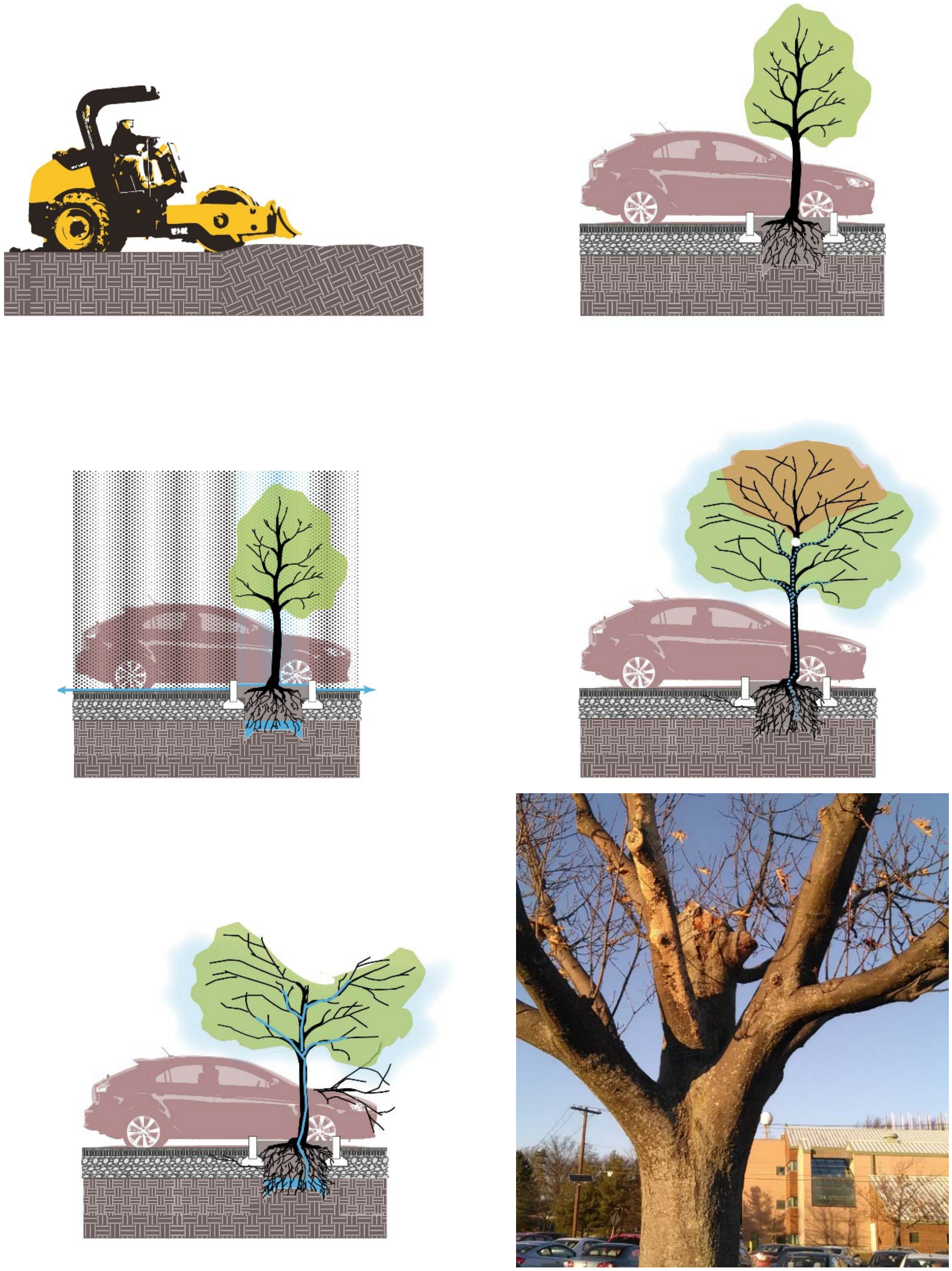


Figure 36: Construction of parking lots require compacted substrates under asphalt and cars further compact soil, which restrict the growth of tree roots and access to water. Trees without adequate water sustain repeated damage to the xylem through cavitation. Eventually, the crown dies and is pruned away. Photo by author.

water and space to grow is larger than that of trees with restricted water and root space. This exponential increase in leaf surface area greatly increases the ecological services provided. More leaf surface area will sequester more carbon, provide more cooling, and capture and transpire more water (Figure 37, Figure 38). Furthermore, trees in less restricted environments have better health and live longer, avoiding the costs of replacement.[73] Several cities, such as Toronto and NYC, have changed ordinances to focus on the quality of tree canopy rather than quantity of trees planted. This research confirms that both types of tree planting will provide ecological services—a tree will transpire an amount relative to size—but designers and clients must be aware of the implications and costs of their pit design choices. Focusing on the quality of tree canopy rather than quantity of trees can provide more ecosystems services per square foot of tree pit.

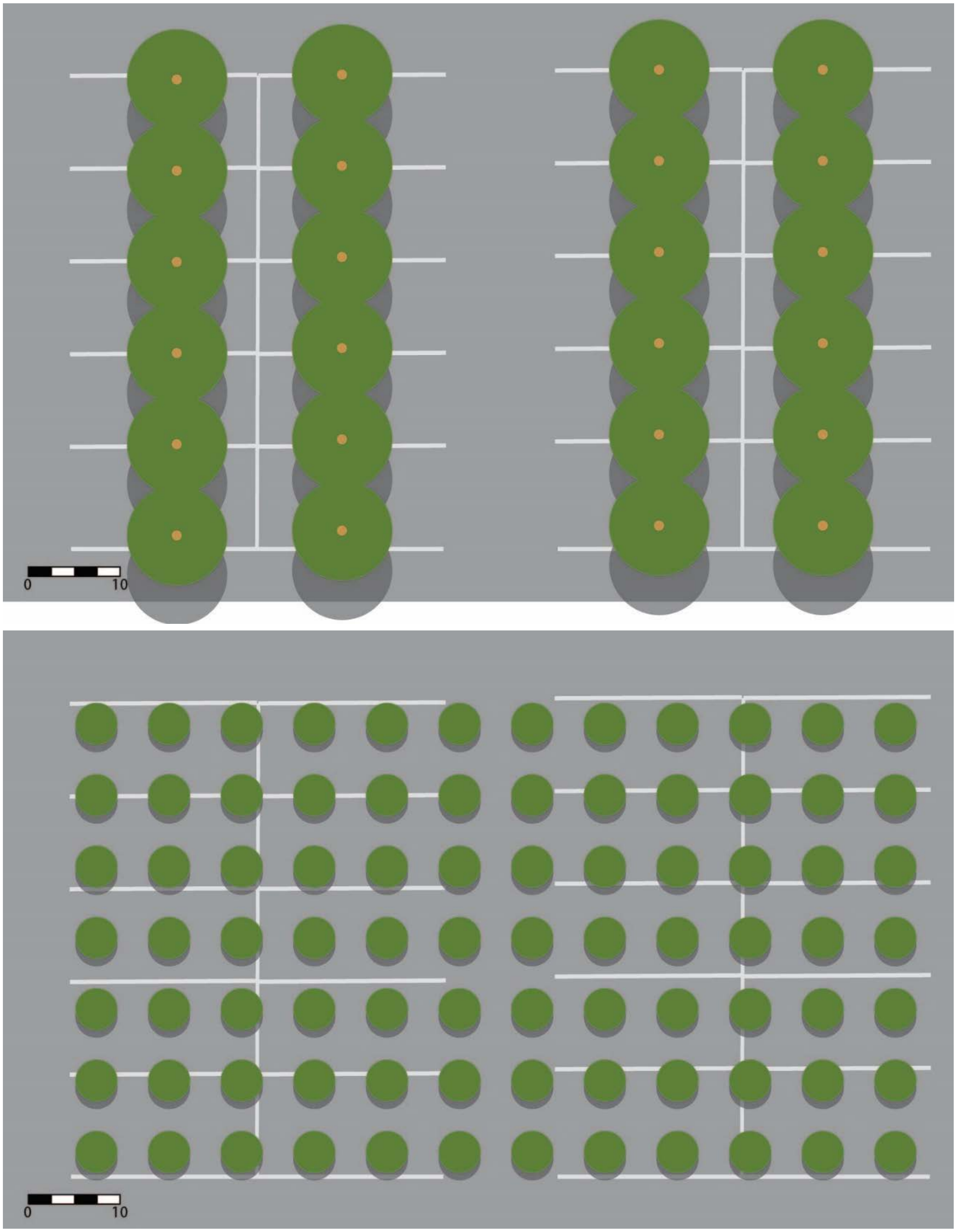


Figure 37: To match the transpiration rate of a mature tree, 24 small trees typical of parking lot pits or 84 shrubs would need to be planted.

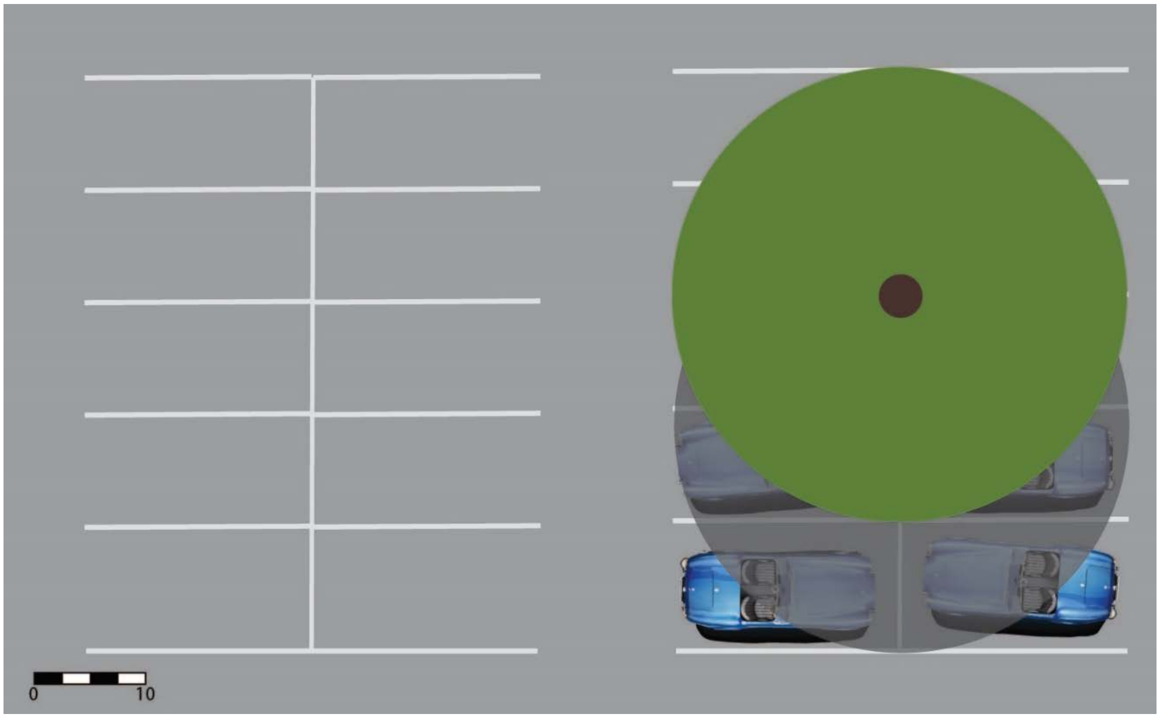


Figure 38: Larger trees provide more ecological services including stormwater capture, carbon sequestration and cooling and shading in a smaller footprint.

Chapter 5: Design

In order to have larger canopies, trees need adequate soil space and water to get to mature size. One of the least expensive ways to provide more water is to allow rainwater to infiltrate into the soil in parking lots. Current practice drains water from surface lots to catch basins, which drain to larger off-site retention or detention basins, or worse, directly into creeks and ponds. These methods of dealing with stormwater reduce the amount of water available to trees and other vegetation and, additionally, allow surface pollution to wash into waterways where it can negatively impact water quality. The United States Environmental Protection Agency enacted the Stormwater Phase II Final Rule in 1999[74] that requires a reduction in the amount of pollution from the initial flow of rain. Application of this rule makes managing stormwater in small onsite infiltration areas an opportunity for designers to create spaces that capture and celebrate rainwater while nourishing plants[75].

Bioretention cells or raingardens, a constructed space filled with quickly draining growing medium and plant material, remove varying levels of pollutants from stormwater. Numerous studies[76] show that most total suspended solids (TSS) and varying levels of heavy metals are removed from stormwater runoff. Bioretention cells that include trees similarly reduce TSS and other pollutants[77], while capturing more water: Not only do trees capture the first 2.54

mm of rainfall (0.1 inch) in their canopy,[78] trees in bioswales transpired 46-72% of water captured, while growing as big or bigger than similar trees in park like settings.[79] Permeable pavement is often recommended for green infrastructure projects. While permeable paving drastically reduces the amount of stormwater runoff, evidence is not clear that trees fare better in pervious paving. Studies of trees under permeable paving compared to impervious paving found root and shoot growth of seedlings had better growth,[80] and young trees grew faster under permeable pavers when there was a deep layer of bedding aggregate[81] or in clay soil with a gravel underlayer.[82] These studies monitored newly planted trees for up to a two year period, and conclusive results will need to wait until the trees reach maturity. Studies on existing 15-18 year old trees that had been newly paved with permeable concrete and asphalt did exhibit more diameter growth than those in conventional paving,[83] but did not photosynthesize or transpire differently[84] and did not have as many fine roots as trees in park like settings, perhaps due to higher heat and lower oxygen in the soil under paving.[85]

Paving changes the chemistry of the soil under the pavement. While the soil directly under impervious pavement tends to collect condensate from the soil, which may attract tree roots, leading to heaving and cracked pavement, permeable pavers with an aggregate subbase have less moisture directly underneath.[86] Pervious pavements without a gravel subbase had similar soil moisture to unpaved soil.[87] The soil under paving whether pervious or impervious tended to have high CO_2 concentrations,[88] higher soil pH and chemical concentrations.[89] Also the complex interactions of soil moisture, pH, nutrients, and soil compaction by cars to the growth of trees are not fully understood.

Numerous studies have calculated the soil volume that would support a mature tree.[90] One recommended soil volume to attain an 8.5 m (28 ft) diameter canopy on a mature tree is 30 m^3 (1000 ft^3) of soil[91] or 2 cubic feet of soil for every square foot of canopy.[92] Using Lindsey and Bassuk's[93] formula for the amount of water used by a 8.5 m^2 (28 ft^2) tree, calculated based on an average 10 days between effective rain and an average Leaf Area Index of 4, a tree pit that is 5.5 m (18 feet) x 3.7 m (13.5 ft) will support this tree, which is roughly the size of one and a half parking spaces.

Suspending pavement over a tree's roots, either using structural soils or an underground framework, allow roots to grow unimpeded with accompanying increased above ground biomass.[94] Additionally, the soils used to fill these systems are not compacted as soils under traditional impervious paving and thus, provide space for stormwater capture.[95] The type of treatment influences the amount of substrate used and the water holding capacity of the soil. There is some evidence that trees using an underground framework grow faster and bigger,[96] but the trees in these studies have not reached maturity, and so the effect of the eventual interaction of the roots with the underground framework have not been assessed.

While standards for sustainable parking lot design have been formulated, they do not address size of planting pit. The *Green Parking Lot Guide* defines green parking as parking lots that have features that address the size and permeability of the parking lot and allow stormwater to infiltrate through the soil, also known as stormwater management best management practices (BMPs).[97] This guide recommends reducing the size of parking spaces and the number of parking spaces,[98] discusses permeable paving options and use,[99] and stormwater management methods[100]. Discussion about vegetation centers on maintenance and benefits of plants, especially the use of native plants for their adaptation to the local environment and accompanying reduced water use[101]. They do not discuss size of bed or effect of heat on plants.

Sustainable Sites Initiative (SITES), a series of recommendations for maintaining and improving healthy landscapes promoted by the Lady Bird Johnson Wildflower Center, the American Society of Landscape Architects, and the US Botanic Garden, advocates several methods for sustainable construction of institutional, commercial and residential buildings and grounds. These include reducing parking spaces by 20%, privileging fuel efficient or carpool vehicles, and minimizing urban heat island effects with vegetation, including reducing the use of impervious and pervious asphalt and concrete which can contribute to higher temperatures[102] The guidelines encourage preservation of existing vegetation, and local sourcing of new plants that are also appropriate for the soil and moisture of the site. No more than 10% of any one species should be planted, 20% of any genus and 30% of any family should be used to minimize pests and diseases associated with monocultures.[103] There are no guidelines for pit size in paved areas for plants.

Sustainable Landscape Construction[104] does address planting pit sizes for trees,[105] but fails to connect water use and planting pit size considerations in their discussion of stormwater capture from paving or paving materials[106]

Using trees to dewater parking lots can combine BMPs for stormwater capture with best practices for tree planting. Comparisons of structural soil and structural grid systems for tree planting, though not novel parking lot tree pit designs, increase the ability to make an accurate assessment of the function of these systems, and is a good use of a parking lot at an academic institution.

Parking Lot Design

To test these tree planting pit designs, a parking lot on Rutgers campus was selected. Rutgers is spread across five campuses in New Brunswick and Piscataway NJ. Parking lot land use ranges from 19% at the downtown New

Brunswick College Avenue Campus to 5% at Livingston campus in Piscataway. Cook-Douglas, where the selected parking lot is, has 6% of its land used for parking. The lower numbers from the Livingston and Cook-Douglas campus benefit from large preserved areas on both campuses. For example, on Cook-Douglas campus, removing the sections of campus that are not as frequented such as the botanic garden Rutgers Gardens, and the fields and pastures of the farm and turf grass program, the percent of land used for parking rises to 13% (Figure 39). Students who commute to all campuses purchase about 14,000 parking permits each year, though this number is far smaller than the number of likely student commuters—28,000.[107] This number also does not include faculty or staff parking space use, which increases the amount of parking needed.

A 1.43 ha (3.5 acre) parking lot on Cook Campus, Lot 98a, was selected based on the relatively large size of the lot, the number of dead or declining trees, and the ineffective stormwater management that includes puddling and wet areas and untreated stormwater that flows into tributaries that empty into the local water supply. Additionally, this lot divides the campus and limits pedestrian traffic between the buildings along Nichol Avenue and the Environmental and Natural Resources building and the farm (Figure 40). A few small trees are growing in planting islands that are filled with compacted soil. Other islands have nothing but gravel covering compacted soil. This lack of

Figure 39: Cook-Douglass campus has many parking lots in the central area of student life (in white). The percentage of parking lot to campus appears small if the large, but less populated areas of campus are included (in green). Map created by author.

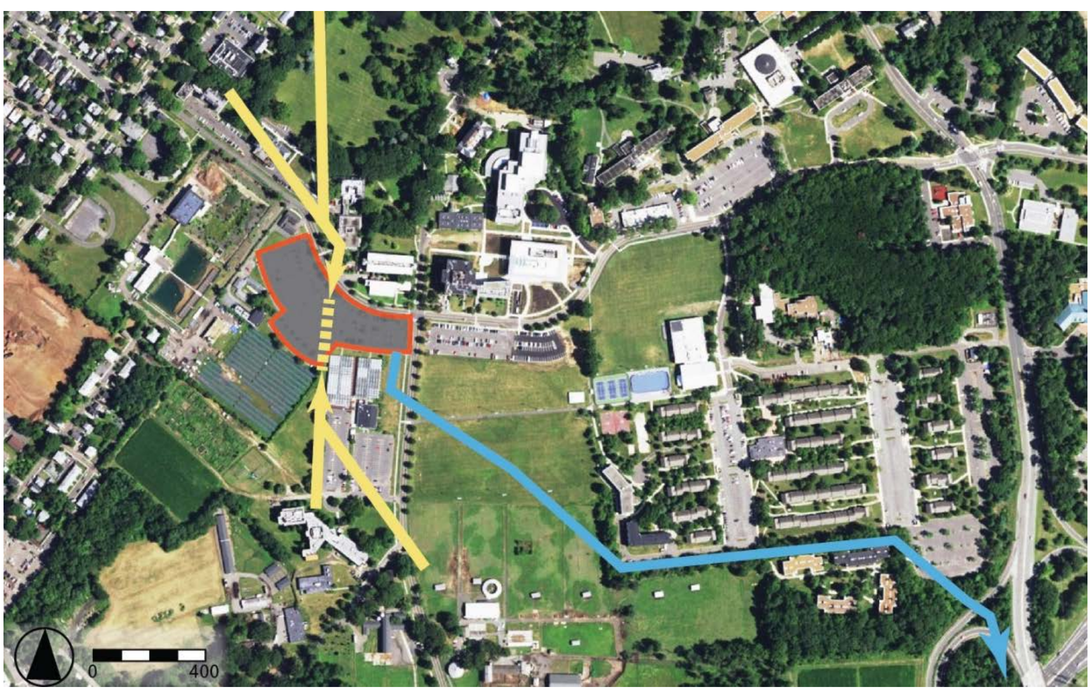


Figure 40: Lot 98a shown in red outline. Yellow lines indicate impeded circulation across campus due to the large parking lot. Blue line shows the direction of water draining to a local tributary of Weston Mill Pond. Map by Google Earth.

vegetation on the lot creates a stark appearance (Figure 41) that does not support the campus' focus on horticulture, environmental resources, agriculture or biology.

Figure 41: Photo of Lot 98a. Little vegetation and lots of cars contribute to the stark appearance of the lot. Photo by author.

Design Concept

Dudley Road, near the northeast corner of the Lot 98a, marks the ridge between the Raritan watershed and the Weston Mill Pond watershed on Cook Campus. Lot 98a has a 1% slope toward seven catch basins that connect, through a series of underground drains, to surface tributaries and retention ponds, including one in Rutgers Gardens, which ultimately empty into Weston Mill Pond. Catchment areas for each drain were drawn based on contours of the parking lot and total runoff was calculated for each area based on the New Jersey water quality storm standard of 31.75 mm (1.25 inches) of rain over two hours[108] (Figure 42). The total amount of water from this storm equals 377 m^3 (13,346 ft^3).

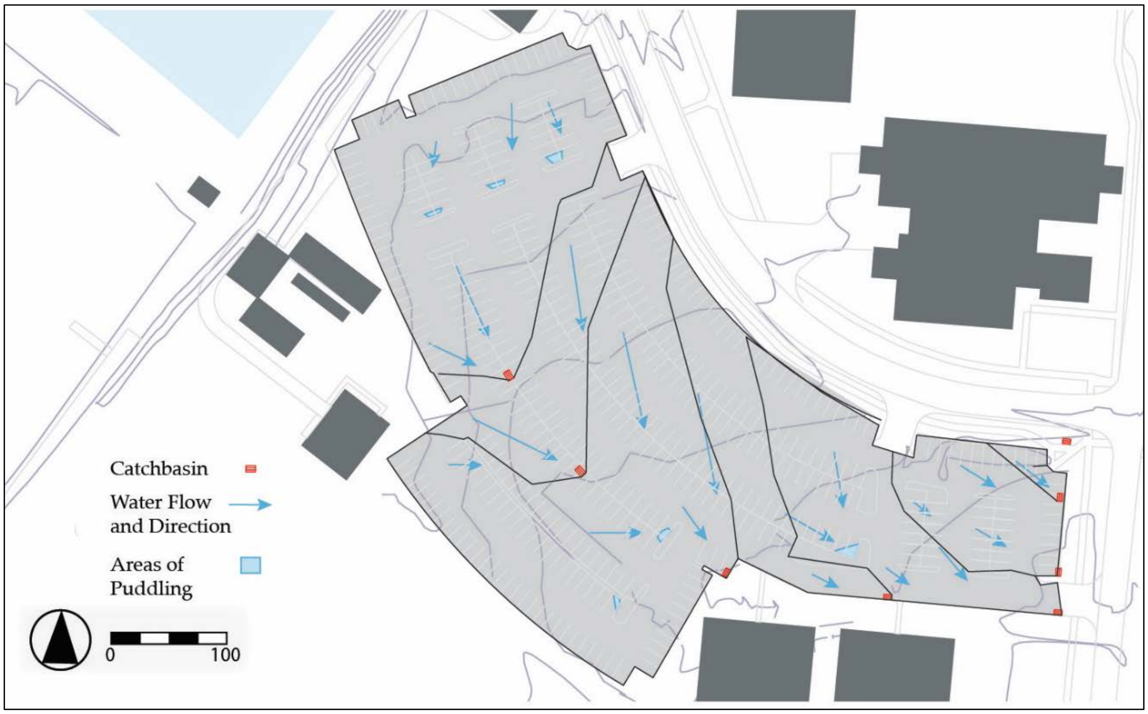


Figure 42: Stormwater drains to 7 catch basins, but frequently puddles on the lot near planting islands.

Point source interventions were designed that will capture immediate rainwater and allow both ground infiltration and water for trees (Figure 43). These interventions can be easily retrofitted with minimal loss of parking spaces. Water availability dictates a plant palette acceptable for parking lots, and provides a demonstration opportunity for plants with interesting qualities to be showcased. Inspiration was drawn from the direction of stormwater flow across the parking lot, with a corresponding xeric and mesic portion depending on the cumulative amount of rainwater infiltrating to the plants (Figure 44, Figure 45).

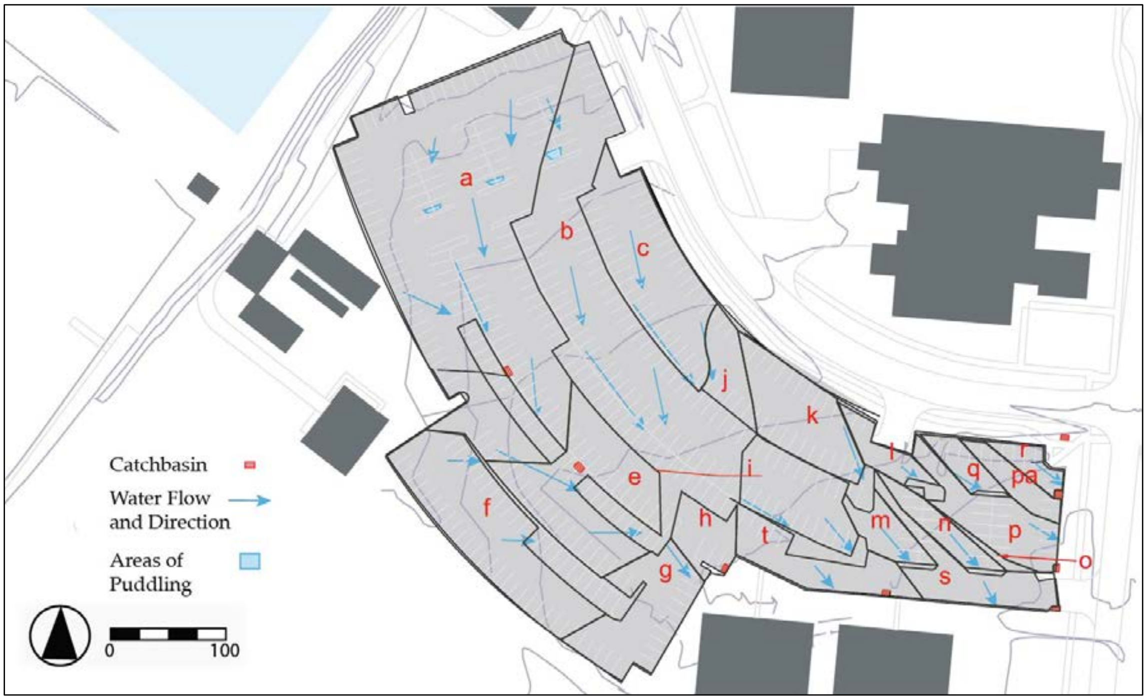


Figure 43: New catchment areas collect stormwater in tree pits and planting islands

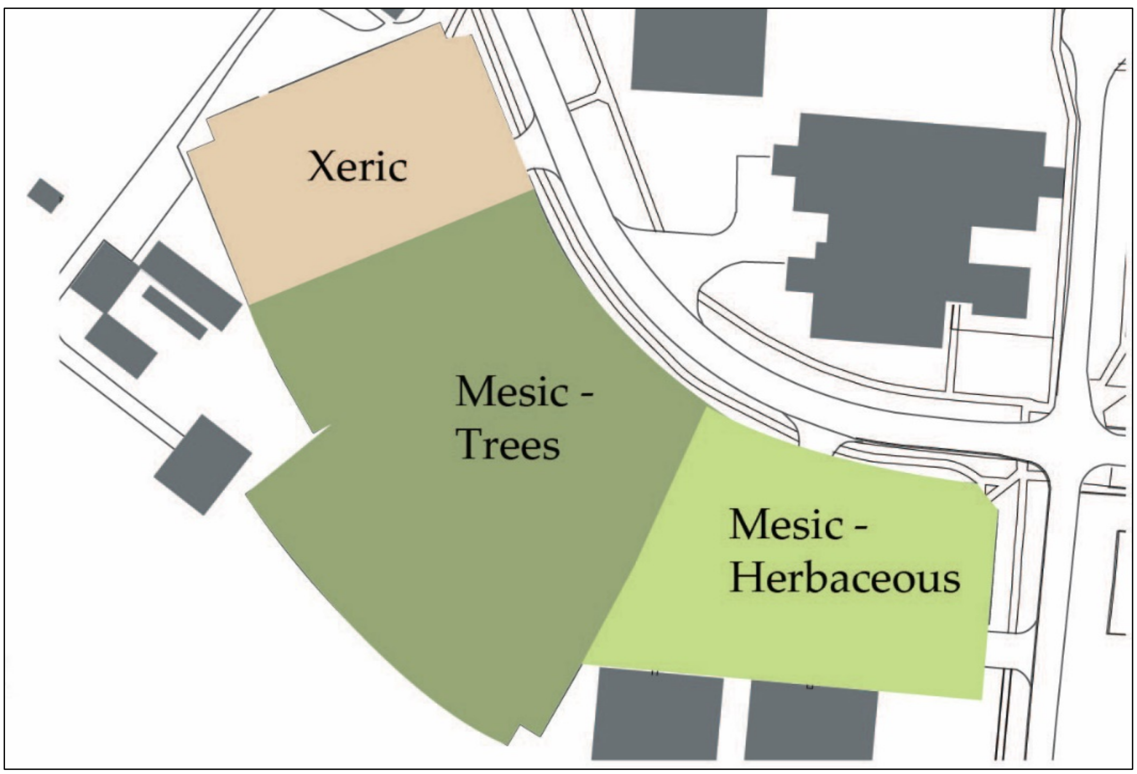


Figure 44: Planting Concept

Figure 45: Lot 98a Plan View

The xeric portion of the lot, at the highest elevation, features plants that typically inhabit dry rocky sites, like coastal dunes or outcroppings. *Rosa rugosa*, *Ceonothus americanus*, *Genestria lydia*, *Yucca flaccida*, *Sedum* spp., *Opuntia humisifera*, and *Eragrostis* spp. tolerate hot, dry conditions (Figure 46, Figure 47).

The Mesic-tree portion of the lot receives more rainwater and features trees that are tolerant of a wide range soil moistures (Figure 48). Additionally

Figure 46: Xeric plantings take advantage of dry infertile soil already in the parking lot planting beds.

trees screen the view of the fenced solar field beyond and visually segment the expanse of the parking lot. Tree pits are sized to accommodate the growth and water use of mature trees. Combined growing pits provide additional room for tree root growth and shared water resources. Structural soils or structural grids support a suspended pavement of permeable pavers that provide parking between trees (Figure 49). Pits for trees are filled with loam soil and underplanted with communities of low growing groundcovers in test plots. These include *Distichlis spicata*, *Rhus aromatica*, *Juniperus* spp., *Elymus hystrix*. *Guem frageroides*, *Narcissus* spp., and *Pycnanthemum* spp.that are arranged to capture pollutants from initial stormwater runoff, provide a living mulch and transition from the xeric zone to the wetter raingardens at the southern end of the parking lot (Figure 50). The concrete pavers are seeded with ruderal vegetation that typically inhabits parking lot cracks and have proven tolerance to a variety of conditions (Figure 51, Figure 52).

Achillea millefolium -
Yarrow

Asclepius tuberosa -
Butterfly Weed

Caryopteris x clandonensis -
Blue Mist Shrub

Ceonothus americanus -
New Jersey Tea

Coreopsis lanceolata -
Lance-leaved Tickseed

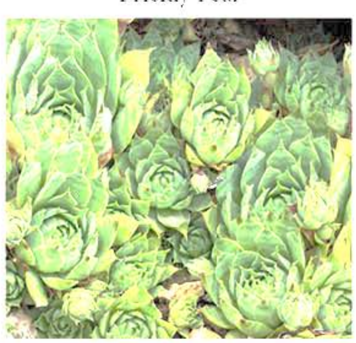
Eragrostis spectibilis -
Purple Lovegrass

Narcissus 'Suzy' -
Jonquils

Opuntia humisifera -
Prickly Pear

Rosa rugosa -
Seaside Rose

Sedum spp.-
Sedums



Sempervivum tectorum -
House Leek

Solidago nemorosa -
Gray Goldenrod

Figure 47: Selected plants from the Xeric section of parking lot, which exhibit high drought tolerance.

Figure 48: Mesic-tree area takes advantage of the largest amount of stormwater runoff to water trees.

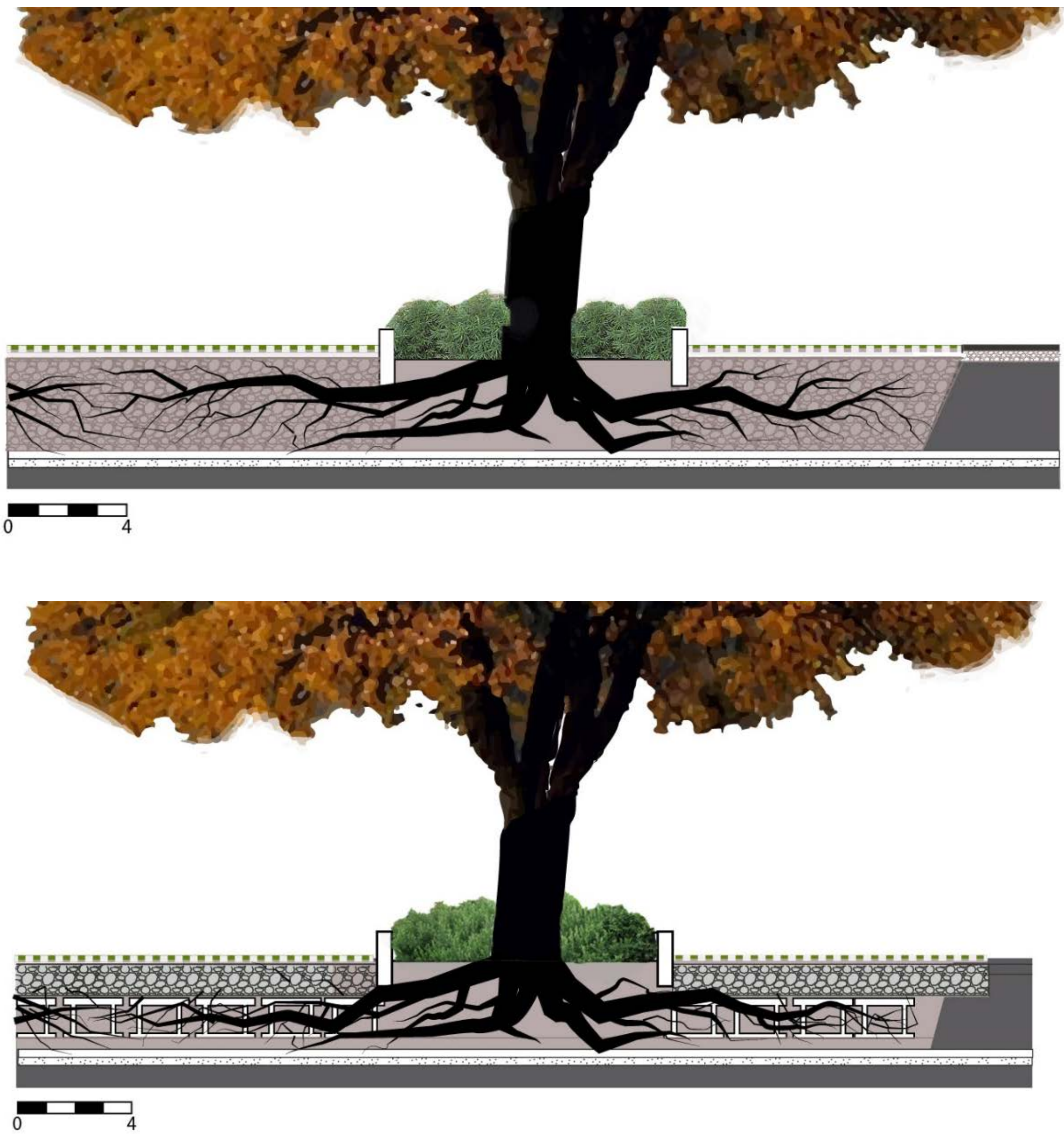


Figure 49: Tree pits filled with structural soil or loam hold up to 9" of rainwater, which is transpired by the trees over several days.

Celtis occidentalis 'Prairie Pride' - Hackberry

Cotinus obovatus - American Smoke Tree

Gymnocladus dioicus 'Espresso' - Kentucky Coffeetree

Maculara pomifera 'Wichita'- Osage Orange

Parrotia persica 'Vanessa' - Persian Parrot Tree

Ulmus parviflora - Lacebark Elm

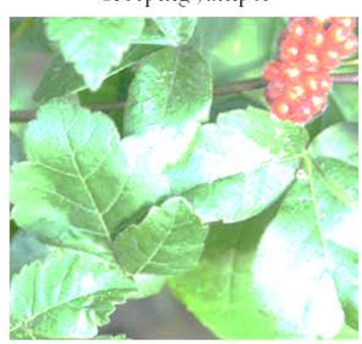
Distichlis spicata - Seaside Grass

Genestria lydia - Lydia Woadwaxen

Juniperus horizonalis - Creeping Juniper

Myrica gale - Sweet Gale

Prunus pulima 'depressa'- Creeping Sand Cherry



Rhus aromatica 'Gro-Lo'- Fragrant Sumac

Figure 50: Selected plants in the Mesic-tree area. Trees are given adequate root space so they can grow to mature size

Figure 51: Permeable pavers are seeded with plants that naturally occur in parking lots—some of these can tolerate being driven over.

Islands which separate parking bays from drive lanes at the southern end of the parking lot tend to capture water already, but result in puddles in the parking lot. Providing curb cuts to allow water infiltration uses the existing built structures to produce stormwater BMPs. Soil will be amended with a faster draining substrate and planted with low growing, raingarden species. The low stature will maintain views of the greenhouses and farm (Figure 53).

A pedestrian walkway was included to connect outlying buildings to the main campus and provide safe passage through the parking lot. This walkway is

Anagallis arvensis -
Scarlet Pimpernel

Cyperus eragrostis-
Umbrella Sedge

Erodium cicutarium - Red
Stem Stork Bill

Linaria canadensis -
Old Field Toadflax

Linaria vulgaris-
Butter and Eggs

Juncus tenuis -
Path Rush

Sanguina procumbens-
Birdseye Pearlwort

Spergularia rubra -
Red Sandspurry

Stellaria media -
Common Chickweed

Veronica arvensis -
Corn Speedwell

Viola cornuta -
Johnny-Jump-Up

Viola soraria -
Common Blue Violet

Figure 52: Selected plants adapted to parking lots—some that can be driven on--are seeded into the concrete pavers.

delineated with cobbled walkways across drive lanes that slow traffic and prioritize the pedestrian (Figure 54, Figure 55).

Figure 53: Mesic-herbaceous area captures rainwater in planting islands.

Figure 54: A path through the parking lot encourages and protects pedestrians.

Plant Selection

Current plants in the parking lot include *Quercus bicolor* (swamp white oaks), *Pinus mug*o (Swiss Mountain Pine) and several *Spiraea japonica*. Planted on the margin, are *Picea* spp., and *Betulus populafolia*. Areas without trees are covered with lawn.

Vegetation chosen for parking lots must be able to tolerate harsh conditions including drought, salt for deicing, high pH soils, and winds. None of the trees studied in this project were selected for planting due to their frequency in many stages of growth on the campus. While *Gleditsia triacnathos* and *Zelkova* meet the requirements for parking lot planting, *Acer rubrum* varies in its tolerance of drought depending on provenance,[109] is less tolerant of high pH or wind [110] or high temperatures under asphalt.[111] Additionally *Gleditsia triacanthos* has an increasing pest load due to overuse.[112]

Trees that are capable of withstanding harsh parking lot conditions, as well as high pH structural soil, include *Celtis occidentalis* (Hackberry), *Gymnocladus dioicus* (Kentucky Coffeetree), *Maclura pomifera* (Osage Orange), *Parrotia persica* (Persian ironwood), *Robinia psuedoacacia* (Black Locust), and *Ulmus parviflora* (Lacebark Elm).[113] These trees, particularly male non-fruiting varieties necessary for parking lot use, are not currently growing on campus or are older

Carex spp.
Sedges

Cephalanthus occidentalis
'Sugar Shack' - Buttonbush

Cyperus spp. - Flatsedges

Juncus effusis -
Soft Rush

Monarda didyma-
Beebalm

Panicum virgatum -
Switchgrass

Pycnanthemum spp. -
Mountain Mint

Senecio smallii -
Small's Ragwort

Schizacryium scoparius -
Little Bluestem

Symphotricum spp.-
Asters

Tridens flavus-
Purpletop

Vernonia spp. -
Ironweed

Figure 55: Mesic-Herbaceous plants are typical of floodplain areas and are tolerant of both inundation and dryness.

trees. Following the SITES Sustainable Guidelines of representing no more than 30% of any genus was selected.

Two out of four shrubs studied were also well represented on campus—*Euonymous* and *Spiraea*, and while *Ilex* glabra also has some specimens on campus, its ability to withstand drought and inundation make it a valuable shrub in bioretention cells. *Rosa rugosa* has few specimens on campus and will be used in the final design. Shrubs that are currently used in parking lots, but are not as well represented on campus include *Juniperus* spp. (Ground cover junipers), and *Myrica pennsylvanica* (Bayberry). Lubell[114] evaluated 6 native shrubs for use in parking lots in Connecticut and found that *Myrica gale* (Sweet Gale), *Comptonia peregrina* (Sweet Fern), and *Cephalanthus occidentalis* (Buttonbush) were as attractive and hardy as *Eunoymus alataus* 'Compacta' and *Berberis thunbergii* in parking lots. *Corylus americana* (American Filbert), and *Diervilla lonicera* (Northern Bush Honeysuckle) also rated highly for attractiveness and hardness, but were slow to establish the first year. *Spiraea tomentosa* (Steeplebush) fared poorly. These studies were conducted in planting zone 5b, and uses plants that would not tolerate the hot summers of Central New Jersey. Shrubs that are potentially able to tolerate parking lot conditions in this area of the US include *Ceonothus americanus* (New Jersey Tea), *Diervilla sessilifolia* (Southern Bush Honeysuckle), *Prunus maritima* (Beach Plum), *Genestria lydia*,

(Lydia Woadwaxen) and *Caryopteris x clandonensis* (Blue Mist Shrub), *Rhus aromatica* (Fragrant Sumac). These species will be used in the parking lot as demonstration species to expand the palette of parking lot plants and provide habitat and pollinator value.

Perennials, gramenoids and annuals are frequently used in bioretention cells and rain gardens near parking lots, but rarely in parking lot islands. Traditional planting techniques use shrubs and trees and occasional grasses, surrounded by mounds of mulch.[115] This design attempts to incorporate plant communities into parking lot plant palettes to provide test plots for living ground covers that may reduce the need for maintenance and mulch, can increase biodiversity, and provide additional habitat and food value for wildlife.

Again, these forbs and grasses need to be tolerant of salt tolerant, drought high pH, of which few studies, but much anecdotal evidence exists in the context of parking lots. *Aster nova an*gliae 'Red Shades' and *Panicum virgatum* had high salt tolerance in bioretention basins.[116] Additional plant selections were gleaned from personal observation, Lauren Frazee's study of ruderal vegetation in active parking lots (pers. comm., 2016),[117] Peter del Tredici's *Wild Urban Plants of the Northeast*,[118] as well the New Jersey Stormwater Best Management Practices Manual.[119] Plant palettes showing type of plant, botanic name, common name, height, and seasonal interest are at Figure 56 to Figure 58.

This design increases the biodiversity of plants in this parking lot, provides habitat and food for wildlife, and incorporates safety measures for better pedestrian access. By providing large planting pits for trees and raingardens in planting islands and adjacent to the lot, all the stormwater from a two year design storm is captured and used to water plants or allowed to infiltrate into the ground.

Xeric Plant Palette															
Genus species	Common	Cultivars	Height	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Shrubs															
Caryopteris x clandonensis	Blue Mist Shrub	Petit Bleu	2.5'												
Ceanothus americanus	New Jersey Tea		2.5'												
Genestria lydia	Lydia Woadwaxen		1.5'												
Rosa rugosa	Saltspray Rose		4'												
Yucca filamentosa	Yucca		2'												
Forbs															
Achillea millefolium	Yarrow		2'												
Achillea millefolium	Yarrow	Paprika	2'												
Asclepius tuberosa	Butterfly Weed		2'												
Aster pilosus	Frost Aster		2'												
Chrysanthemum leucanthemum	Oxeye Daisy		1'												
Coreopsis lanceolata	Lance-leaved Tickseed	Sterntaler	2'												
Erigeron annuus	Annual Fleabane		3'												
Narcissus spp.	Daffodil	Minnow	8"												
Narcissus spp.	Daffodil	Suzy'	15"												
Narcissus spp.	Daffodil	Dickcissel	12"												
Opuntia humisifera	Prickly Pear		6"												
Pycanthemum tenuifolium	Narrowleaf Mountain Mint		2.5'												
Pycnanthemum incanum	Hoary Mountain Mint		2'												
Pycnanthemum muticum	Clustered Mountain Mint		2'												
Pycnanthemum tenuifolium	Slender Mountain Mint		2'												
Sedum kamtschaticum	Sedum		6"												
Sedum ochroleucum	Sedum, Red Wiggle		3"												
Sedum spurium	Sedum, Red Carpet		4"												
Sempervivum tectorum	House Leek		3"												
Solidago nemorosa	Gray Goldenrod		1.5'												
Symphotricum racemosum	Oldfield Aster														
Viola cornuta	Johnny-Jump-Up		6"												
Gramenoids															
Danthonia spicata	Poverty Grass		1'												
Eragrostis spectiblis	Purple Lovegrass		1'												
Schizacryium scoparius	Little Bluestem		2.5'												
Cyperus dentatus	Toothed Flatsedge		1'					f							
Cyperus eragrostis	Umbrella Flatsedge		1'												
Cyperus strigosus	Strawcolored Flatsedge		1'												
Juncus bufonius	Toad Rush		4"												

Figure 56: Xeric Plant Palette

Mesic-Trees Plant Palette															
Genus species	Common	Cultivars	Height	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trees															
Celtis occidentalis	Hackberry	Prairie Pride	50'												
Cotinus obovatus	American Smoketree		25'												
Gymnocladus dioicus	Kentucky Coffeetree	Espresso	60'												
Maculara pomifera	Osage orange	Wichita	30'												
Parrotia persica	Parrot tree	Ruby Vase	30'	attracti	bark	flowers/leaves									
Shrubs															
Juniperus conferta	Juniper		1'												
Juniperus horizontalis	Juniper		6"												
Myrica gale	Sweet Gale		2.5'												
Rhus aromatica	Fragrant Sumac		1.5'												
Comptonia peregrina	Sweetfern		3'												
Prunus pumila	Creeping Sand Cherry	var. depressa	2'												
Forbs															
Chrysogonum virginianum	Green and gold		6"												
Solidago sempervirens	Seaside Goldenrod		3'												
Symphotricum novae-anglai	New England Aster		4'												
Viola soraria	Common Blue Violet														
Senecio aureaus (Packera)	Golden Ragwort		1'												
Senecio smallii	Small's Ragwort		1'												
Waldensteinia frageroides	Barren Strawberry		6"												
Zizia aptera	Heartleaf Alexander		1'												
Zizia aurea	Golden Alexander		2'												
Gramenoids															
Distichlis spicata	Seaside Grass		1'												
Carex bicknellii	Prairie Sedge		1'												
Cyperus dentatus	Toothed Flatsedge		1'					f							
Cyperus eragrostis	Umbrella Flatsedge		1'												
Cyperus strigosus	Strawcolored Flatsedge		1'												
Juncus bufonius	Toad Rush		4"												

Crack Growers--in pavers															
Genus species	Common	Cultivars	Height	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Anagallis arvensis	Scarlet Pimpernel		1"												
Arenaria serpyllifolia	Thyme-leaved Sandwort		1"												
Cerastium fontanum	Mouse Ear Chickweed		1"												
Erodium cicutarium	Red Stem Stork Bill		4"												
Euphorbia maculata	Prostrate Spurge		1"												
Linaria canadensis	Old Field Toadflax		4"												
Linaria vulgaris	Yellow Toadflax		8"												
Lotus corniculatus	Birdsfoot Trefoil		6"												
Medicago lupulina	Black Medic		1"												
Oxalis stricta	Yellow Wood Sorrel		3"												
Polygonum convulvulus	Prostrate Knotweed		1"												
Portulaca oleracea	Purslane		1"												
Saguina procumbens	Birdseye Pearlwort		1"												
Scleranthus annuus	Knawel		1"												
Spergularia rubra	Red Sandspurry		1"												
Stellaria media	Common Chickweed		1"												
Veronica arvensis	Corn Speedwell		1"												
Viola sororia	Blue Violet		6"												

Figure 57: Mesic-Tree Plant Palette and Paver Plant Palette

Mesic-Herbaceous Plant Palette															
Genus species	Common	Cultivars	Height	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Shrubs															
Myrica gale	Sweet Gale		2.5'												
Cephalanthus occidentalis	Buttonbush	Sugarshack	3'												
Ilex verticillata	Winterberry Holly	red sprite	3.5'												
Ilex verticillata	Winterberry Holly	Raritan Chief	3.5'												
Ilex verticillata	Winterberry Holly	Shaver	3.5'												
Myrica pennsylvanica	Bayberry		6'												
Clethra alnifolia	Clethra		6'												
Forbs															
Erigeron annuus	Annual Fleabane		3'												
Eupatorium hyssopifolium	Thoroughwort		2'												
Mondara didyma	Beebalm		3'												
Narcissus spp.	Daffodil	Minnow	8"												
Narcissus spp.	Daffodil	Suzy'	15"												
Narcissus spp.	Daffodil	Dickcissel	12"												
Pycnanthemum incanum	Hoary Mountain Mint		2'												
Pycnanthemum muticum	Clustered Mountain Mint		2'												
Pycnanthemum tenuifolium	Slender Mountain Mint		2'												
Solidago nemorosa	Gray Goldenrod		1.5'												
Solidago sempervirens	Seaside Goldenrod		3'												
Symphotricum novae-anglai	New England Aster		4'												
Symphotricum racemosum	Oldfield Aster														
Vernonia glauca	Upland Ironweed		3'												
Senecio aureaus (Packera)	Golden Ragwort		1'												
Senecio smallii	Small's Ragwort		1'												
Waldensteinia frageroides	Barren Strawberry		6"												
Zizia aptera	Heartleaf Alexander		1'												
Zizia aurea	Golden Alexander		2'												
Gramenoids															
Panicum virgatum	Switchgrass	Rostrahlbusch	3'												
Panicum virgatum	Switchgrass	Shenendoah	2'												
Schizacryium littorale	Cape May Bluestem														
Tridens flavus	Purpletop		2.5'												
Carex bicknellii	Prairie Sedge		1'												
Carex emoryii	Emory's Sedge														
Carex rosea	Curly Wood Sedge		1'												
Carex socialis	Social Sedge		1'												
Carex texensis	Catlin Sedge		6"												
Cyperus dentatus	Toothed Flatsedge		1'					f							
Cyperus eragrostis	Umbrella Flatsedge		1'												
Cyperus strigosus	Strawcolored Flatsedge		1'												
Juncus bufonius	Toad Rush		4"												
Juncus effusis	Soft Rush		1'												

Figure 58: Mesic-Herbaceous Plant Palette

Chapter Six: Conclusion

This study found that vegetation in parking lots does provide an ecological service of dewatering storm runoff. Leaves from trees in parking lots strips and pits transpire at a similar rate to leaves from trees in parks. However, trees with constricted root growth are much smaller than those with no restriction to root growth. Shrubs in parking lots and parks had only modest differences in appearance of health, though they used water at different rates. Trees in parking lots can support large amounts of biomass if given adequate space and water to grow. Increasing biomass has the benefit of increasing the amount of stormwater that is captured and transpired to the atmosphere. Incorporating mature trees into parking lots provides the most stormwater capture per area of surface used, an important consideration in parking lot design. Adequate space for root growth must be provided for mature tree growth.

The use of structural soils or structural grids to support pavement reduces root constriction of trees, allows stormwater capture even when trees are not yet full grown. Ultimately, these systems allow infiltration into the ground near parking lot plants and provide water for tree growth in areas with adequate rain volume. Zoning ordinances that require a ratio of trees to cars or percent shading by trees should instead ensure that trees are able to grow to full maturity to provide maximum ecological services per dollar spent. Ordinances that focus on quality of tree rather than quantity of trees should be considered.

A design alternative to trees is to plant vegetation that can tolerate the water availability at the site. Planting parking lots with vegetation typical of coastal areas or rocky sites uses a plant's adaptation to stress. Using floodplain plants to slow and filter stormwater provides water quality benefits. Ruderal vegetation of parking lots has proven tolerance to harsh conditions.

Suburban landscapes are built for cars, and, while urban policies have created more choice in transportation for city dwellers, little public will and anemic reception of government policy has not yet altered the dominance of automobile transportation in suburban locations. Low cost reliable public transportation, fewer drivers, and safe streets for pedestrians and bicyclists should be addressed through grassroots organization and government policies like Complete Streets, higher gas taxes, and changes in ordinances that require huge parking lots that are barely used. While we work for change on transportation, parking lots remain a necessary evil. But they don't have to be barren soulless place. Landscape architects can design modest interventions that provide stormwater capture, support vegetation growth and increase habitat and food for wildlife.

Appendix

Many examples of sustainable parking lots exist, which provided not only design ideas but an opportunity to experience walking, driving and parking in these lots. Of the lots I visited, most were relatively small—185-464 m^2 (2000 to 5000 ft^2)—but two were part of larger parking lots—20.2 ha (50 acres) of which 1.8 ha (4.5 acres) were paved with grass or gravel, and a 0.8 ha (2 acre) lot, which had 37 m^2 (400 ft^2) of bioswale. These case studies were selected because they provided interesting ways of using vegetation and/or pavement in parking lots.

Westfarms Mall

The largest lot (20.2 ha or 50 acres) is at Westfarms Mall in Hartford, CT, which uses a permeable paving system for its 1.8 ha (4.5 acres) overflow parking. In 1995, Westfarms Mall added an expansion and needed to meet regulations for both parking and stormwater management. General Manager, Kevin Keenan chose to use GrassPave2,[120] which is a permeable grass paving system that can withstand high loads from cars and trucks, to provide the extra parking needed for the six days per year when the mall was busiest (Figure 59). GrassPave2 is comprised of a compacted sandy base layer of depths that vary according to loading standards, topped by a layer of permeable grids filled with concrete sand and growing mix into which grass is seeded. This system is designed for light to moderate traffic (2-6 passes per day). Stormwater and pollutants are captured and filtered through the sand layers.[121]

Figure 59: Westfarms Mall overflow parking paved in grass and gravel pavers. Photo by author.

Keenan reports that the first two plantings of grass seed washed out in heavy rainstorms and the company chose to lay bluegrass sod in an effort to meet opening day demand. The sod was pressed into the grid forms much like a cookie cutter. The parking area is used during the Christmas shopping rush—about 6 days per year—and then restricted during the rest of the year with gates.

When not in use, this lot looks like ordinary lawn with trees and grass, and the system is irrigated and maintained as a standard lawn. In winter, snow is removed by plows with rollers or skids on the plow. Keenan reports that he believes the installation and maintenance costs are comparable to a traditional asphalt paving system, but has no documented proof. Grasspavers require excavation of a foundation layer and regular mowing, but don't need the drainage system and maintenance required by an asphalt system. An added benefit is that the mall does not look empty as an asphalted lot would during low season.

Problems with the system include the limited number of car passes per day, and additionally the accumulation of thatch and organic matter which, over time, bury the grid which supports the cars. The cumulative effect of these drawbacks led to the parking aisles becoming mucky, and in 2012, the aisles were replaced with GravelPave, a similar grid based driveway filled with gravel. Invisible Structures has provided a white paper explaining how to avoid accumulation of debris.

In an informal survey, trees in the asphalt parking lot looked noticeably smaller than the trees in the grass paved section of the parking, though they were planted later than the trees in the parking lot (Figure 60).

Dia Beacon

Dia Beacon, in Beacon, NY, used many small trees to attain canopy coverage in their parking lot, rather than create larger pits for big trees (Figure

61). Dia Beacon, in Beacon, NY, opened in 2003 as a contemporary art museum housed in a renovated Nabisco box-printing factory. The designers—architects OpenOffice and artist Robert Irwin—planned the parking lot as a grand entrance complementary to the building. This 0.4 ha (1 acre) conventional asphalt parking lot features allees of *Carpinus betulus* 'Fastigiata' (Fastigiate European Hornbeam), and doubled parking bays separated by Malus spp. (flowering crabapple) with an underplanting of *Panicum virgatum* "Ruby Ribbons" (Ruby Ribbons switchgrass). The trees are approximately 5 meters tall and wide which provides shade for the cars parked on either side of the planting bed. The planting beds are surrounded by Cor-Ten steel curbs. (Figure 62)

Figure 60: Trees with adjacent to the permeable paving appear larger than same aged trees in asphalt paving. Photo by author.

Figure 61: Dia Beacon used small flowering crabapples (Malus spp.) to provide shade. Photo by author.

Figure 62: Frequently spaced planting pits filled with switchgrass and small trees feels lush and shady. Photo by author.

The central drive aisle provides a direct view of the front door to the museum framed by the low trees. Cars are parked at an angle and one way loops on either side of the central drive provide easy wayfinding and an easily accessible drop off and exit. The relatively low stature and close canopy of the trees feels a bit claustrophobic, but does provide good shade during the heat of a summer afternoon, when many people visit the museum.

A series of parking lots in Portland, OR provide case studies in retrofitting parking lots for stormwater capture and tree growth, which can immediately lessen the impact of stormwater without having to wait for the lot to be resurfaced or renovated.

Lot 10

Portland Community College Sylvania Campus's (PCC) Lot 10 was retrofit with a suspended pavement supported by structural soil in an attempt to provide tree cover without any loss of parking (Figure 63). This campus is similar to Rutgers with a large number of commuters and, thus, a need for parking lots. Thirty-seven m^2 (400 ft^2) of pavement, centered on 8 doubled parking spaces, was removed and the soil excavated to at least 69 cm (27 in). A drain and catch basin were installed, which led to a rain garden retrofitted into an aisle end (Figure 64). The entire trench was filled with amended native and structural soil and then four feet on either side of the trench was then repaved with impervious asphalt.

Figure 63: Portland Community College demonstration of porous asphalt, structural soil and small planting pits. Depave volunteers removed the asphalt for this project. Photo by author.

Figure 64: Raingarden retrofitted into the end island. Photo by author.

Two trees (*Pseudotsuga menziesii*, Douglas Fir) were planted in this tree pit. Finally, wheel stops were installed to prevent cars from driving into the loose gravel and soil in the pit. Wheel stops installed at each site were supposed to have feet that would allow stormwater to run underneath them, but funds prevented this type of stop from being installed. Unfortunately, the runoff became channelized between the stop and eroded the soil in the pit. Also, students who normally used the lot either drove over the stops or backed into the parking spaces which could cause damage to the trees. The trees seem to be growing well, though there were no control trees for comparison.

Depave

Lot 10's raingarden is a project from Depave, which is a grassroots organization who partners with community groups to pry up parking lots in order to install green infrastructure or play spaces. Up to 100 volunteers manually pry up squares of asphalt, cart them to transport containers, which, ultimately, are taken to an asphalt recycler. After the asphalt is removed, the volunteers may prepare the soil, plant vegetation and install site furniture, or Depave staff excavate the new planting bed and blows in soil, which volunteers plant at a later date.

Depave's projects include parking lot retrofits with no loss of spaces, reduction of parking spaces with more space for vegetation, or complete removal of parking lots to manage stormwater or create play spaces and gardens [122].

Depave began in 2006 when Arif Khan and his friend Kasandra Griffin jackhammered up the concrete covering his backyard and planted a garden. Observing that Portland, OR had lots of paving in places that could use green infrastructure, Kahn and Griffin began a not for profit focused on "freeing soil." They wrote grants for funds from state-based stormwater management funds, but consider the community building aspect of the asphalt removal work key to their success. They now employ a full time director and part time volunteer coordinator and the model has been adopted by other cities in Canada and the US. (pers. comm., 2016)

Community organizations, churchs, schools, etc. and Depave work together to recruit volunteers for an event. Depave provides the technical pavement removal and planting expertise. "We are a full service landscape company," remarked Eric Rosewell, Executive Director of Depave (pers. comm., 2016). The director and volunteer crew leaders organize and execute the initial steps of depaving—soil testing, site selection, dumpster ordering and saw cutting the asphalt into 1-2′ squares. During a Depaving event, crew leaders monitor the volunteer workers. The volunteer organizer works with the partner organization to make the depaving day an event complete with catering, music, and activities for the volunteers. Some other exemplary projects from the 55 parking lots transformed by Depave include sites where green infrastructure was installed. While all of the projects were aimed at stormwater management, some added value by including plants for wildlife and people, playgrounds or murals.

The author participated in a Depaving event at Human Solutions Family Resource Center, which is a transitional shelter for homeless families in Northeast Portland. The building had recently been converted from a strip club with a large parking lot that people cut through to access a side street. According to Director of Development, Andy Miller, “having children outside playing while people are driving through at 30 miles per hour was not going to work for us” (pers. comm., 2016). Human Solutions staff and clients, local business and community groups volunteered to remove asphalt on a Saturday morning. Depave crew leaders had sawn the asphalt into 2 foot squares, some with small triangles cut into one corner (Figure 65). After a few introductions and exercises led by directors, crew leaders explained how to pry up concrete, emphasizing safety and carrying precautions. Volunteers grabbed a pry bar or wheelbarrow and began working, removing the majority of the asphalt in 2 hours. After a lunch break and some relaxation, the volunteers tackled the remaining sections

Figure 65: Asphalt to be removed by volunteers with Depave. Photo by author.

of concrete (Figure 66). Planting would take place in the fall, when plants could be established more easily.

Calvary Church had a large parking lot which was used only once or twice a week, but served as cut-through for drivers avoiding a traffic light. Depave volunteers broke up 4500 ft^2 (418 m^2) of asphalt and installed four large rain gardens (Figure 67), including one that blocked the cut-through. Speedbumps serve a dual purpose to cut speed and to channel water into the raingardens (Figure 68). A wide variety of native plants were installed including many with berries and seeds to feed local birds. One well place plant selection is

Figure 66: Removing the final pieces of asphalt. Photo by author.

the use of *Mahonia* under a razor wire fence, which provides a prickly deterrent to climbing the fence next door.

Lewis Elementary volunteers removed 2200 ft^2 (204 m^2) of asphalt playground to install two large rain gardens and several raised bed gardens (Figure 69). Subsequently the school has removed more asphalt and installed a log playground.

At St Mary's Ethiopian Church, the building sat several feet below the grade of the street on a site completely covered with impervious surfaces. Poor grading in the parking lot directed stormwater directly into the basement of the

Figure 67: Depaving created a large center island for planting at Calvary Church, Portland. Photo by author.

Figure 68: A speed bump, bottom right, channels water to a rain garden. Photo by author.

church. Fifty volunteers removed 2400 ft^2 (223 m^2) of paving and planted a raingarden strategically to capture the runoff. The basement has not flooded since the garden was installed (Figure 70).

123

Figure 69: Lewis school in Portland removed pavement to add a raingarden. Photo by author.

There are many more examples of better ways to incorporate plants into parking lots than the ubiquitous slab of asphalt. Lack of knowledge, funds and apathy limit the ability to integrate beauty, functionality, and ecological services into landscapes. Education and community building can turn blank asphalt canvases into places of beauty, habitat and function.

Figure 70: A large raingarden planted in removed asphalt mitigated flooding at St. Mary's Ethiopian Church, Portland. Photo by author.

Endnotes

[1] International Society of Arboriculture, "Guidelines for Developing and Evaluating Tree Ordinances," October 31, 2001, http://www.isa-arbor.com/education/resources/educ_TreeOrdinanceGuidelines.pdf.
[2] Borough of Princeton, "Zoning Code," accessed April 9, 2016, http://www.princetonnj.gov/zoning/docs/Boro-Zoning-Code.pdf.
[3] Maryland-National Capital Park and Planning Commission, "Prince George's County Landscape Manual" (Prince George's County, MD: Maryland-National Capital Park and Planning Commission, December 2010), 56, http://www.pgplanning.org/Assets/Planning/Development+Review/Prince+George$!e2$!80$!99s+County+Landscape+Manual/Prince+George$!27s+County+Landscape+Manual+-+December+2010.pdf.
[4] Cincinnati OARM, "Green Parking Lot Resource Guide," July 2008, 12, http://nepis.epa.gov/Exe/ZyPDF.cgi/P100D97A.PDF?Dockey=P100D97A.PDF; Eran Ben-Joseph, *ReThinking a Lot: The Design and Culture of Parking* (Cambridge, Mass: MIT Press, 2012), 37.
[5] David J. Nowak, Daniel E. Crane, and Jack C. Stevens, "Air Pollution Removal by Urban Trees and Shrubs in the United States," *Urban Forestry & Urban Greening* 4, no. 3–4 (April 3, 2006): 115–23, doi:10.1016/j.ufug.2006.01.007.
[6] Chang Zhao and Heather A. Sander, "Quantifying and Mapping the Supply of and Demand for Carbon Storage and Sequestration Service from Urban Trees," *PLoS ONE* 10, no. 8 (August 28, 2015): 1–31, doi:10.1371/journal.pone.0136392.
[7] D. Armson, P. Stringer, and A. R. Ennos, "The Effect of Tree Shade and Grass on Surface and Globe Temperatures in an Urban Area," *Urban Forestry & Urban Greening* 11, no. 3 (2012): 245–55, doi:10.1016/j.ufug.2012.05.002.
[8] Limor Shashua-Bar, David Pearlmutter, and Evyatar Erell, "The Cooling Efficiency of Urban Landscape Strategies in a Hot Dry Climate," *Landscape and Urban Planning* 92, no. 3–4 (September 30, 2009): 179–86, doi:10.1016/j.landurbplan.2009.04.005.
[9] E. G. McPherson and J. Muchnick, "Effect of Street Tree Shade on Asphalt Concrete Pavement Performance.," *Journal of Architectural Education (1984-)* 31, no. 6 (November 2005): 303–10.
[10] D. Armson, P. Stringer, and A. R. Ennos, "The Effect of Street Trees and Amenity Grass on Urban Surface Water Runoff in Manchester, UK," *Urban Forestry & Urban Greening* 12, no. 3 (2013): 282–86, doi:10.1016/j.ufug.2013.04.001.
[11] E. Gregory McPherson, David J. Nowak, and Rowan Rowntree, *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* / (Radnor, PA: Northeastern Forest Experiment Station, 1994), 78, 91, http://hdl.handle.net/2027/umn.31951d02995937i.
[12] Jennifer Mullaney, Terry Lucke, and Stephen J. Trueman, "A Review of Benefits and Challenges in Growing Street Trees in Paved Urban Environments," *Landscape and Urban Planning* 134 (February 2015): 157–66, doi:10.1016/j.landurbplan.2014.10.013.
[13] Lara Roman, "How Many Trees Are Enough? Tree Death and the Urban Caonpy," *Scenario Journal* 04 (Spring 2014), https://www.fs.fed.us/nrs/pubs/jrnl/2014/nrs_2014_roman_001.pdf.
[14] Kim Coder, "Soil Compaction and Trees: Causes, Symptoms and Effects," July 2000, https://www.extension.iastate.edu/forestry/publications/PDF_files/for00-003.pdf; Arthur T. DeGaetano and Stephen R. Hudson, "Specification of Soil Volume and Irrigation Frequency for Urban Trees," *Journal of Arboriculture* 26, no. 3 (May 2000): 142–51; J. Grabosky and N. Bassuk,

---

"Seventeen Years' Growth of Street Trees in Structural Soil Compared with a Tree Lawn in New York City," *Urban Forestry & Urban Greening* 16 (2016): 103–9, doi:10.1016/j.ufug.2016.02.002; Patricia Lindsey and Nina Bassuk, "Specifying Soil Volumes to Meet the Water Needs of Mature Urban Street Trees and Trees in Containers," *Journal of Arboriculture* 17, no. 6 (June 1991): 141–49.
[15] James Urban, "Nursery: The Root of the Problem," *Landscape Architecture Magazine*, April 2013.
[16] Justin Morgenroth, Bernardo Santos, and Brad Cadwallader, "Conflicts between Landscape Trees and Lawn Maintenance Equipment – The First Look at an Urban Epidemic," *Urban Forestry & Urban Greening* 14, no. 4 (2015): 1054–58, doi:10.1016/j.ufug.2015.10.002.
[17] Richard G. Allen et al., *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements* (Rome: Food and Agriculture Organization of the United Nations, 1998), http://www.fao.org/docrep/x0490e/x0490e04.htm; Paul J. Kramer, *Water Relations of Plants* (New York, N.Y: Academic Press, 1983), 292.
[18] Nathalie Breda et al., "Temperate Forest Trees and Stands under Severe Drought: A Review of Ecophysiological Responses, Adaptation Processes and Long-Term Consequences," *Annals of Forest Science* 63 (2006): 625–44.
[19] Kramer, *Water Relations of Plants*, 298.
[20] Shashua-Bar, Pearlmutter, and Erell, "The Cooling Efficiency of Urban Landscape Strategies in a Hot Dry Climate."
[21] Breda et al., "Temperate Forest Trees and Stands under Severe Drought: A Review of Ecophysiological Responses, Adaptation Processes and Long-Term Consequences," 636.
[22] Allen et al., *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements*.
[23] Ibid.
[24] W. Ehlers and M. Goss, eds., *Water Dynamics in Plant Production* (Wallingford: CABI, 2003), 21–27, 81, doi:10.1079/9780851996943.0000; Kramer, *Water Relations of Plants*, 191–96.
[25] Kramer, *Water Relations of Plants*, 50–51, 196.
[26] Ehlers and Goss, *Water Dynamics in Plant Production*, 12, 64–67.
[27] Ibid., 12, 26.
[28] Kramer, *Water Relations of Plants*, 128.
[29] Ehlers and Goss, *Water Dynamics in Plant Production*, 80–81.
[30] Ibid., 21, 87.
[31] R. J. Ansley et al., "Stem Flow and Porometer Measurements of Transpiration from Honey Mesquite [Prosopis Glandulosa," *Journal of Experimental Botany* 45, no. 275 (June 1994): 847–56; G. Ferrara and J. A. Flore, "Comparison between Different Methods for Measuring Transpiration in Potted Apple Trees," *Biologia Plantarum* 46, no. 1 (2003): 41–47; Robert W. Pearcy, E. Detlef Schulze, and Reiner Zimmermann, "Chapter 8: Measurement of Transpiration and Leaf Conductance," in *Plant Physiological Ecology* (Springer Science+Business Media B.V., 1989), 148–58.
[32] Stephen S. O. Burgess and Todd E. Dawson, "Using Branch and Basal Trunk Sap Flow Measurements to Estimate Whole-Plant Water Capacitance: A Caution," *Plant & Soil* 305, no. 1/2 (April 2008): 5–13, doi:10.1007/s11104-007-9378-2; Pearcy, Schulze, and Zimmermann, "Chapter 8: Measurement of Transpiration and Leaf Conductance," 153.
[33] S. Catovsky, N.m. Holbrook, and F.a. Bazzaz, "Coupling Whole-Tree Transpiration and Canopy Photosynthesis in Coniferous and Broad-Leaved Tree Species," *Canadian Journal of Forest Research* 32, no. 2 (February 2002): 295; Janina Konarska et al., "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City," *International Journal of Biometeorology* 60, no. 1 (June 6, 2015): 159–72, doi:10.1007/s00484-015-1014-x.
[34] Catovsky, Holbrook, and Bazzaz, "Coupling Whole-Tree Transpiration and Canopy Photosynthesis in Coniferous and Broad-Leaved Tree Species."
[35] Konarska et al., "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City."

[36] Catovsky, Holbrook, and Bazzaz, "Coupling Whole-Tree Transpiration and Canopy Photosynthesis in Coniferous and Broad-Leaved Tree Species."
[37] Konarska et al., "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City."
[38] Heather R. McCarthy, Diane E. Pataki, and G. Darrel Jenerette, "Plant Water-Use Efficiency as a Metric of Urban Ecosystem Services," *Ecological Applications* 21, no. 8 (December 1, 2011): 3115–27, doi:10.1890/11-0048.1.
[39] Sten Gillner et al., "Role of Street Trees in Mitigating Effects of Heat and Drought at Highly Sealed Urban Sites," *Landscape and Urban Planning* 143 (November 2015): 33–42, doi:10.1016/j.landurbplan.2015.06.005.
[40] Konarska et al., "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City," 170.
[41] Konarska et al., "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City"; Yoko Osone et al., "Responses of Gas-Exchange Rates and Water Relations to Annual Fluctuations of Weather in Three Species of Urban Street Trees," *Tree Physiology* 34, no. 10 (October 1, 2014): 1056–68, doi:10.1093/treephys/tpu086.
[42] Jennifer Mullaney et al., "The Effect of Permeable Pavements with an Underlying Base Layer on the Ecophysiological Status of Urban Trees," *Urban Forestry & Urban Greening* 14, no. 3 (2015): 686–93, doi:10.1016/j.ufug.2015.06.008.
[43] Jens Dahlhausen et al., "Tree Species and Their Space Requirements in an Urban Environment," *Forests* 7, no. x (2016): 17; Jason Grabosky and Edward Gilman, "Measurement and Prediction of Tree Growth Reduction from Tree Planting Space Design in Established Parking Lots," *Journal of Arboriculture* 30, no. 3 (May 2004): 154–64; Jessica R. Sanders and Jason C. Grabosky, "20 Years Later: Does Reduced Soil Area Change Overall Tree Growth?," *Urban Forestry & Urban Greening* 13 (2014): 295–303; Oana Pohoață Lupu and Lucia Draghia, "The Relationship between Growth Prediction and Soil Surface for Three Urban Tree Species in Romania" (Draft journal article, University of Agricultural Sciences and Veterinary Medicine of Iași, Faculty of Horticulture, 3 Mihail Sadoveanu Alley, Iași, 700490, Romania, 2016).
[44] Patricia Lindsey and Nina Bassuk, "Redesigning the Urban Forest from the Ground Below: A New Approach to Specifiying Adequate Soil Volumes for Street Trees," *Arboricultural Journal* 16 (1992): 25–39.
[45] DeGaetano and Hudson, "Specification of Soil Volume and Irrigation Frequency for Urban Trees."
[46] Coder, "Soil Compaction and Trees: Causes, Symptoms and Effects."
[47] Roger Kjelgren and Thayne Montague, "Urban Tree Transpiration over Turf and Asphalt Surfaces," *Atmospheric Environment*, Conference on the Benefits of the Urban Forest, 32, no. 1 (January 1, 1998): 35–41, doi:10.1016/S1352-2310(97)00177-5.
[48] Howard G. Halverson and Donald F. Potts, "Water Requirements of Honeylocust (Gleditsia Triacanthos F. Inermis) in the Urban Forest." (USDA-Forest Service, 1981), https://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/scanned/OCR/ne_rp487.pdf.
[49] Osone et al., "Responses of Gas-Exchange Rates and Water Relations to Annual Fluctuations of Weather in Three Species of Urban Street Trees."
[50] Bureau of Transportation Data and Safety, Roadway Systems Section, "New Jersey's Roadway Mileage and Daily VMT by Functional Classification Distributed by County" (NJ Department of Transportation, 2015), http://www.state.nj.us/transportation/refdata/roadway/pdf/hpms2015/VMTFCC_15.pdf.
[51] "Office of the New Jersey State Climatologist," 2017, http://climate.rutgers.edu/stateclim/?section=njcp&target=NJCnormex.

[52] Aiguo Dai, Kevin E. Trenberth, and Taotao Qian, "A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming," *Journal of Hydrometeorology* 5, no. 6 (December 2004): 1117–30.
[53] Beryl Robichaud, Karl Anderson, and Beryl Robichaud, *Plant Communities of New Jersey: A Study in Landscape Diversity* (New Brunswick, N.J: Rutgers University Press, 1994).
[54] "USDA Plant Hardiness Zone Map" (Agricultural Research Service, US Department of Agriculture., 2012), http://planthardiness.ars.usda.gov; "AHS Plant Heat Zone Map" (American Horticultural Society, 2017), http://www.ahs.org/gardening-resources/gardening-maps/heat-zone-map.
[55] Jerry Bond, *Urban Tree Health* (Geneva, NY: Forest Analytics LLC, 2012).
[56] LI-COR Biosciences, "LI-COR 6400," User's Manual (Lincoln, Nebraska: LI-COR, Inc., 2012), https://www.licor.com/documents/s8zyqu2vwndny903qutg.
[57] "New Brunswick, NJ," *New Jersey Weather and Climate Network*, 2016, http://www.njweather.org/station/1101.
[58] *Minitab*, version 2017, Windows (State College, PA: Minitab Inc., 2017).
[59] Lindsey and Bassuk, "Redesigning the Urban Forest from the Ground Below: A New Approach to Specifiying Adequate Soil Volumes for Street Trees."
[60] Patricia Lindsey and Nina L. Bassuk, "A Nondestructive Image Analysis Technique for Estimating Whole-Tree Leaf Area," *HortTechnology* 2, no. 1 (March 1992): 66–72; Paula J. Peper and E. Gregory McPherson, "Evaluation of Four Methods for Estimating Leaf Area of Isolated Trees," *Urban Forestry & Urban Greening* 2, no. 1 (January 1, 2003): 19–29, doi:10.1078/1618-8667-00020.
[61] Mark S. Thorne et al., "Evaluation of a Technique for Measuring Canopy Volume of Shrubs," *Journal of Range Management* 55, no. 3 (2002): 235–41, doi:10.2307/4003129.
[62] Pearcy, Schulze, and Zimmermann, "Chapter 8: Measurement of Transpiration and Leaf Conductance," 139.
[63] Ibid., 153.
[64] Kim Coder, "Construction Damage Assessments: Trees and Sites" (University of Georgia, October 1996), https://www.extension.iastate.edu/forestry/publications/PDF_files/for96-039a.pdf.
[65] Kramer, *Water Relations of Plants*, 306.
[66] Oscar Godoy, José Pires de Lemos-Filho, and Fernando Valladares, "Invasive Species Can Handle Higher Leaf Temperature under Water Stress than Mediterranean Natives," *Environmental and Experimental Botany* 71, no. 2 (June 2011): 207–14, doi:10.1016/j.envexpbot.2010.12.001.
[67] William H. Schlesinger and Brian F. Chabot, "The Use of Water and Minerals by Evergreen and Deciduous Shrubs in Okefenokee Swamp," *Botanical Gazette* 138, no. 4 (1977): 490–97.
[68] Jan Cermak et al., "Urban Tree Root Systems and Their Survival near Houses Analyzed Using Ground Penetrating Radar and Sap Flow Techniques," *Plant and Soil* 219 (2000): 103–16; Halverson and Potts, "Water Requirements of Honeylocust (Gleditsia Triacanthos F. Inermis) in the Urban Forest."; Diane E. Pataki et al., "Transpiration of Urban Forests in the Los Angeles Metropolitan Area," *Ecological Applications* 21, no. 3 (April 1, 2011): 661–77, doi:10.1890/09-1717.1.
[69] Schlesinger and Chabot, "The Use of Water and Minerals by Evergreen and Deciduous Shrubs in Okefenokee Swamp."
[70] Michael Dirr, *Manual of Woody Landscape Plants: Their Identification, Ornamental Characteristics, Culture, Propagation, and Uses*, 6th ed (Champaign, Ill: Stipes Pub, 2009).
[71] Grabosky and Gilman, "Measurement and Prediction of Tree Growth Reduction from Tree Planting Space Design in Established Parking Lots"; Sanders and Grabosky, "20 Years Later: Does Reduced Soil Area Change Overall Tree Growth?"

---

[72] Breda et al., "Temperate Forest Trees and Stands under Severe Drought: A Review of Ecophysiological Responses, Adaptation Processes and Long-Term Consequences."
[73] McPherson, Nowak, and Rowntree, *Chicago's Urban Forest Ecosystem*.
[74] US Environmental Protection Agency, "Stormwater Phase II Rule: An Overview," Fact Sheet (US Environmental Protection Agency, rev 2005), https://www.epa.gov/sites/production/files/2015-11/documents/fact1-0.pdf.
[75] Stuart Echols and Eliza Pennypacker, "Artful Rainwater Design" (webinar, Penn State University, May 26, 2015), https://meeting.psu.edu/p6inrex6c54/?proto=true.
[76] Erik S. Bedan and John C. Clausen, "Stormwater Runoff Quality And Quantity From Traditional And Low Impact Development Watersheds," *Journal Of The American Water Resources Association* 45, no. 4 (August 2008): 998–1009; J. Choi et al., "Application of a Gravel Wetland System for Treatment of Parking Lot Runoff," *Desalination and Water Treatment* 51, no. 19–21 (01 2013): 4129–37, doi:10.1080/19443994.2013.781109; C. Glass and S. Bissouma, "Evaluation of a Parking Lot Bioretention Cell for Removal of Stormwater Pollutants," *Ecosystems and Sustainable Development* 81 (May 2005): 699–708.
[77] Franz Kevin F. Geronimo, Marla C. Maniquiz-Redillas, and Lee-Hyung Kim, "Treatment of Parking Lot Runoff by a Tree Box Filter," *Desalination and Water Treatment* 51, no. 19–21 (May 2013): 4044–49, doi:10.1080/19443994.2013.781099; Qingfu Xiao and E. Gregory McPherson, "Performance of Engineered Soil and Trees in a Parking Lot Bioswale," *Urban Water Journal* 8, no. 4 (August 1, 2011): 241–53, doi:10.1080/1573062X.2011.596213.
[78] DeGaetano and Hudson, "Specification of Soil Volume and Irrigation Frequency for Urban Trees."
[79] Bryant C. Scharenbroch, Justin Morgenroth, and Brian Maule, "Tree Species Suitability to Bioswales and Impact on the Urban Water Budget," *Journal of Environmental Quality* 45, no. 1 (January 2016): 199–206, doi:10.2134/jeq2015.01.0060.
[80] Justin Morgenroth, Graeme Buchan, and Bryant C. Scharenbroch, "Belowground Effects of Porous pavements—Soil Moisture and Chemical Properties," *Ecological Engineering* 51 (February 2013): 221–28, doi:10.1016/j.ecoleng.2012.12.041.
[81] T. Lucke et al., "Using Permeable Pavements to Promote Street Tree Health, to Minimize Pavement Damage and to Reduce Stormwater Flows" (2th International Conference on Urban Drainage, Porto Alegre, Brazil, 2011).
[82] Mullaney et al., "The Effect of Permeable Pavements with an Underlying Base Layer on the Ecophysiological Status of Urban Trees."
[83] W. Todd Watson and Astrid Volder, "Use of Pervious Pavements to Preserve Urban Forests and Urban Watersheds" (Texas A&M University, 2007).
[84] Astrid Volder, Todd Watson, and Bhavana Viswanathan, "Potential Use of Pervious Concrete for Maintaining Existing Mature Trees during and after Urban Development," *Urban Forestry & Urban Greening* 8, no. 4 (2009): 249–56, doi:10.1016/j.ufug.2009.08.006.
[85] Bhavana Viswanathan et al., "Impervious and Pervious Pavements Increase Soil CO_2 Concentrations and Reduce Root Production of American Sweetgum (Liquidambar Styraciflua)," *Urban Forestry & Urban Greening* 10, no. 2 (2011): 133–39, doi:10.1016/j.ufug.2011.01.001.
[86] Lucke et al., "Using Permeable Pavements to Promote Street Tree Health, to Minimize Pavement Damage and to Reduce Stormwater Flows."
[87] Morgenroth, Buchan, and Scharenbroch, "Belowground Effects of Porous pavements—Soil Moisture and Chemical Properties."
[88] Viswanathan et al., "Impervious and Pervious Pavements Increase Soil CO_2 Concentrations and Reduce Root Production of American Sweetgum (Liquidambar Styraciflua)."

[89] Morgenroth, Buchan, and Scharenbroch, "Belowground Effects of Porous pavements—Soil Moisture and Chemical Properties."
[90] Coder, "Soil Compaction and Trees: Causes, Symptoms and Effects"; DeGaetano and Hudson, "Specification of Soil Volume and Irrigation Frequency for Urban Trees"; Grabosky and Bassuk, "Seventeen Years' Growth of Street Trees in Structural Soil Compared with a Tree Lawn in New York City"; Lindsey and Bassuk, "Specifying Soil Volumes to Meet the Water Needs of Mature Urban Street Trees and Trees in Containers."
[91] James Urban, "Will the Trees Grow?" (American Society of Landscape Architects, New Orleans, LA, 2016).
[92] E. Thomas Smiley, "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement" (American Society of Landscape Architects, New Orleans, LA, 2016).
[93] Lindsey and Bassuk, "Redesigning the Urban Forest from the Ground Below: A New Approach to Specifiying Adequate Soil Volumes for Street Trees."
[94] Grabosky and Bassuk, "Seventeen Years' Growth of Street Trees in Structural Soil Compared with a Tree Lawn in New York City"; Jonathan L. Page, Ryan J. Winston, and William F. Hunt III, "Soils beneath Suspended Pavements: An Opportunity for Stormwater Control and Treatment," *Ecological Engineering* 82 (September 2015): 40–48, doi:10.1016/j.ecoleng.2015.04.060; E. Thomas Smiley et al., "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement," *Arboriculture & Urban Forestry* 32, no. 4 (2006): 164–69; Smiley, "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement."
[95] Nina Bassuk, Robert Pine, and James Urban, "The Great Soils Debate Handout: Structural Soils Under Pavement," 2010, https://www.asla.org/uploadedFiles/CMS/Meetings_and_Events/2010_Annual_Meeting_Handouts/Sat-B1The%20Great%20Soil%20Debate_Structural%20Soils%20Under%20Pavement.pdf; Page, Winston, and Hunt III, "Soils beneath Suspended Pavements."
[96] Smiley, "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement."
[97] Cincinnati OARM, "Green Parking Lot Resource Guide," 1.
[98] Ibid., 7,10.
[99] Ibi
d., 22–29.
[100] Ibid., 15–17.
[101] Ibid., 35–40.
[102] Sustainable SITES, "Rating System For Sustainable Land Design and Development" (Green Business Certification Inc., 2014), 49–50.
[103] Ibid., 23–24, 42, 48.
[104] J. William Thompson and Kim Sorvig, *Sustainable Landscape Construction: A Guide to Green Building Outdoors* (Washington, D.C: Island Press, 2000).
[105] Ibid., 118.
[106] Ibid., 173–91.
[107] Sustainable Endowments Institute, "Green Report Card 2011-Rutgers University," *The College Sustainability Report Card*, 2011, http://www.greenreportcard.org/report-card-2011/schools/rutgers-universitynew-brunswick/surveys/campus-survey.html#climate; Avalon Zoppo, "Rutgers Rakes in Nearly $5 Million from Parking Violations," *MY CENTRAL JERSEY*, August 7, 2016, http://www.mycentraljersey.com/story/news/education/college/rutgers/2016/08/07/rutgers-rakes-nearly-5-million-parking-violations/88009580/.

---

[108] Sandra A. Blick, Fred Kelly, and Joseph J. Skupien, *New Jersey Stormwater Best Management Practices Manual*, 5th ed. (Trenton, NJ: New Jersey Department of Environmental Protection, 2016), http://www.njstormwater.org/bmp_manual/NJ_SWBMP_5%20print.pdf.
[109] W. L. Bauerle et al., “Abscisic Acid Synthesis in Acer Rubrum L. Leaves—A Vapor-Pressure-Deficit-Mediated Response,” *Journal of the American Society for Horticultural Science* 129, no. 2 (March 1, 2004): 182–87.
[110] Dirr, *Manual of Woody Landscape Plants*.
[111] William R. Graves, “Urban Soil Temperatures and Their Potential Impact on Tree Growth,” *Journal of Arboriculture* 20, no. 1 (January 1994): 24–27.
[112] US Forest Service, “Gleditsia Triacanthos L,” accessed March 6, 2017, https://www.na.fs.fed.us/Spfo/pubs/silvics_manual/volume_2/gleditsia/triacanthos.htm.
[113] Nina L. Bassuk, Deanna F. Curtis, and Barb Neal, *Recommended Urban Trees* (Urban Horticulture Institute, Cornell University, 1993), http://www.hort.cornell.edu/uhi/outreach/recurbtree/.
[114] Jessica D. Lubell, “Evaluating Landscape Performance of Six Native Shrubs as Alternatives to Invasive Exotics,” *Horttechnology* 23, no. 1 (February 2013): 119–25.
[115] Thomas Rainer and Claudia West, *Planting in a post-wild world: designing plant communities for resilient landscapes*, 2015, 44.
[116] Chris Denich, Andrea Bradford, and Jennifer Drake, “Bioretention: Assessing Effects of Winter Salt and Aggregate Application on Plant Health, Media Clogging and Effluent Quality,” *Water Quality Research Journal of Canada* 48, no. 4 (November 1, 2013): 387–99, doi:10.2166/wqrjc.2013.065.
[117] Chris Martine, *Extreme Weeds of Parking Lots® : Plants Are Cool, Too! Episode 6*, 2015, https://www.youtube.com/watch?v=HpstofPFX0I.
[118] Peter Del Tredici, “The Flora of the Future: Wild Urban Plants,” *Places Journal*, accessed February 16, 2015, https://placesjournal.org/article/the-flora-of-the-future/.
[119] Blick, Kelly, and Skupien, *New Jersey Stormwater Best Management Practices Manual*.
[120] Invisible Structures, GrassPave2, issued 1993.
[121] Invisible Structures, “GrassPave2 and GravelPave2,” 2006, http://www.invisiblestructures.com/wp-content/uploads/2016/05/GPGV_brochure.pdf.
[122] Depave, “Depave. From Parking Lots to Paradise,” 2016, http://depave.org/about/.

References

"AHS Plant Heat Zone Map." American Horticultural Society, 2017. http://www.ahs.org/gardening-resources/gardening-maps/heat-zone-map.

Allen, Richard G., Luis S. Pereira, Dirk Raes, and Martin Smith. *Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements*. Rome: Food and Agriculture Organization of the United Nations, 1998. http://www.fao.org/docrep/x0490e/x0490e04.htm.

Ansley, R. J., W. A. Dugas, M. L. Heuer, and B. A. Trevino. "Stem Flow and Porometer Measurements of Transpiration from Honey Mesquite [Prosopis Glandulosa." *Journal of Experimental Botany* 45, no. 275 (June 1994): 847–56.

Armson, D., P. Stringer, and A. R. Ennos. "The Effect of Street Trees and Amenity Grass on Urban Surface Water Runoff in Manchester, UK." *Urban Forestry & Urban Greening* 12, no. 3 (2013): 282–86. doi:10.1016/j.ufug.2013.04.001.

———. "The Effect of Tree Shade and Grass on Surface and Globe Temperatures in an Urban Area." *Urban Forestry & Urban Greening* 11, no. 3 (2012): 245–55. doi:10.1016/j.ufug.2012.05.002.

Bassuk, Nina L., Deanna F. Curtis, and Barb Neal. *Recommended Urban Trees*. Urban Horticulture Institute, Cornell University, 1993. http://www.hort.cornell.edu/uhi/outreach/recurbtree/.

Bassuk, Nina, Robert Pine, and James Urban. "The Great Soils Debate Handout: Structural Soils Under Pavement," 2010. https://www.asla.org/uploadedFiles/CMS/Meetings_and_Events/2010_Annual_Meeting_Handouts/Sat-B1The%20Great%20Soil%20Debate_Structural%20Soils%20Under%20Pavement.pdf.

Bauerle, W. L., T. H. Whitlow, T. L. Setter, and F. M. Vermeylen. "Abscisic Acid Synthesis in Acer Rubrum L. Leaves—A Vapor-Pressure-Deficit-Mediated Response." *Journal of the American Society for Horticultural Science* 129, no. 2 (March 1, 2004): 182–87.

Bedan, Erik S., and John C. Clausen. "Stormwater Runoff Quality And Quantity From Traditional And Low Impact Development Watersheds." *Journal Of The American Water Resources Association* 45, no. 4 (August 2008): 998–1009.

Ben-Joseph, Eran. *ReThinking a Lot: The Design and Culture of Parking*. Cambridge, Mass: MIT Press, 2012.

Blick, Sandra A., Fred Kelly, and Joseph J. Skupien. *New Jersey Stormwater Best Management Practices Manual*. 5th ed. Trenton, NJ: New Jersey Department of Environmental Protection, 2016. http://www.njstormwater.org/bmp_manual/NJ_SWBMP_5%20print.pdf.

Bond, Jerry. *Urban Tree Health*. Geneva, NY: Forest Analytics LLC, 2012.

Borough of Princeton. Zoning Code. Accessed April 9, 2016. http://www.princetonnj.gov/zoning/docs/Boro-Zoning-Code.pdf.

Breda, Nathalie, Roland Huc, Andre Granier, and Erwin Dreyer. "Temperate Forest Trees and Stands under Severe Drought: A Review of Ecophysiological Responses, Adaptation Processes and Long-Term Consequences." *Annals of Forest Science* 63 (2006): 625–44.

Bureau of Transportation Data and Safety, Roadway Systems Section. "New Jersey's Roadway Mileage and Daily VMT by Functional Classification Distributed by County." NJ Department of Transportation, 2015. http://www.state.nj.us/transportation/refdata/roadway/pdf/hpms2015/VMTFCC_15.pdf.

Burgess, Stephen S. O., and Todd E. Dawson. "Using Branch and Basal Trunk Sap Flow Measurements to Estimate Whole-Plant Water Capacitance: A Caution." *Plant & Soil* 305, no. 1/2 (April 2008): 5–13. doi:10.1007/s11104-007-9378-2.

Catovsky, S., N.m. Holbrook, and F.a. Bazzaz. "Coupling Whole-Tree Transpiration and Canopy Photosynthesis in Coniferous and Broad-Leaved Tree Species." *Canadian Journal of Forest Research* 32, no. 2 (February 2002): 295.

Cermak, Jan, Jiri Hruska, Milena Martinkova, and Prax Alois. "Urban Tree Root Systems and Their Survival near Houses Analyzed Using Ground Penetrating Radar and Sap Flow Techniques." *Plant and Soil* 219 (2000): 103–16.

Choi, J., M.C. Maniquiz-Redillas, S. Lee, J.M.R. Mercado, and L.-H. Kim. "Application of a Gravel Wetland System for Treatment of Parking Lot Runoff." *Desalination and Water Treatment* 51, no. 19–21 (01 2013): 4129–37. doi:10.1080/19443994.2013.781109.

Cincinnati OARM. "Green Parking Lot Resource Guide," July 2008. http://nepis.epa.gov/Exe/ZyPDF.cgi/P100D97A.PDF?Dockey=P100D97A.PDF.

Clemson, Brian. "Parking Lot Information," June 13, 2016.

Coder, Kim. "Construction Damage Assessments: Trees and Sites." University of Georgia, October 1996. https://www.extension.iastate.edu/forestry/publications/PDF_files/for96-039a.pdf.

———. “Soil Compaction and Trees: Causes, Symptoms and Effects,” July 2000. https://www.extension.iastate.edu/forestry/publications/PDF_files/for00-003.pdf.

Dahlhausen, Jens, Peter Biber, Thomas Rötzer, Enno Uhl, and Hans Pretzsch. “Tree Species and Their Space Requirements in an Urban Environment.” *Forests* 7, no. x (2016): 17.

Dai, Aiguo, Kevin E. Trenberth, and Taotao Qian. “A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming.” *Journal of Hydrometeorology* 5, no. 6 (December 2004): 1117–30.

DeGaetano, Arthur T., and Stephen R. Hudson. “Specification of Soil Volume and Irrigation Frequency for Urban Trees.” *Journal of Arboriculture* 26, no. 3 (May 2000): 142–51.

Del Tredici, Peter. “The Flora of the Future: Wild Urban Plants.” *Places Journal*. Accessed February 16, 2015. https://placesjournal.org/article/the-flora-of-the-future/.

Denich, Chris, Andrea Bradford, and Jennifer Drake. “Bioretention: Assessing Effects of Winter Salt and Aggregate Application on Plant Health, Media Clogging and Effluent Quality.” *Water Quality Research Journal of Canada* 48, no. 4 (November 1, 2013): 387–99. doi:10.2166/wqrjc.2013.065.

Depave. “Depave. From Parking Lots to Paradise,” 2016. http://depave.org/about/.

Dirr, Michael. *Manual of Woody Landscape Plants: Their Identification, Ornamental Characteristics, Culture, Propagation, and Uses*. 6th ed. Champaign, Ill: Stipes Pub, 2009.

Echols, Stuart, and Eliza Pennypacker. “Artful Rainwater Design.” Webinar, Penn State University, May 26, 2015. https://meeting.psu.edu/p6inrex6c54/?proto=true.

Ehlers, W., and M. Goss, eds. *Water Dynamics in Plant Production*. Wallingford: CABI, 2003. doi:10.1079/9780851996943.0000.

Ferrara, G., and J. A. Flore. “Comparison between Different Methods for Measuring Transpiration in Potted Apple Trees.” *Biologia Plantarum* 46, no. 1 (2003): 41–47.

Geronimo, Franz Kevin F., Marla C. Maniquiz-Redillas, and Lee-Hyung Kim. “Treatment of Parking Lot Runoff by a Tree Box Filter.” *Desalination and Water Treatment* 51, no. 19–21 (May 2013): 4044–49. doi:10.1080/19443994.2013.781099.

Gillner, Sten, Juliane Vogt, Andreas Tharang, Sebastian Dettmann, and Andreas Roloff. “Role of Street Trees in Mitigating Effects of Heat and Drought at

Highly Sealed Urban Sites." *Landscape and Urban Planning* 143 (November 2015): 33–42. doi:10.1016/j.landurbplan.2015.06.005.

Glass, C., and S. Bissouma. "Evaluation of a Parking Lot Bioretention Cell for Removal of Stormwater Pollutants." *Ecosystems and Sustainable Development* 81 (May 2005): 699–708.

Godoy, Oscar, José Pires de Lemos-Filho, and Fernando Valladares. "Invasive Species Can Handle Higher Leaf Temperature under Water Stress than Mediterranean Natives." *Environmental and Experimental Botany* 71, no. 2 (June 2011): 207–14. doi:10.1016/j.envexpbot.2010.12.001.

Grabosky, J., and N. Bassuk. "Seventeen Years' Growth of Street Trees in Structural Soil Compared with a Tree Lawn in New York City." *Urban Forestry & Urban Greening* 16 (2016): 103–9. doi:10.1016/j.ufug.2016.02.002.

Grabosky, Jason, and Edward Gilman. "Measurement and Prediction of Tree Growth Reduction from Tree Planting Space Design in Established Parking Lots." *Journal of Arboriculture* 30, no. 3 (May 2004): 154–64.

Graves, William R. "Urban Soil Temperatures and Their Potential Impact on Tree Growth." *Journal of Arboriculture* 20, no. 1 (January 1994): 24–27.

Halverson, Howard G., and Donald F. Potts. "Water Requirements of Honeylocust (Gleditsia Triacanthos F. Inermis) in the Urban Forest." USDA-Forest Service, 1981. https://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/scanned/OCR/ne_rp487.pdf.

International Society of Arboriculture. "Guidelines for Developing and Evaluating Tree Ordinances," October 31, 2001. http://www.isa-arbor.com/education/resources/educ_TreeOrdinanceGuidelines.pdf.

Invisible Structures. GrassPave2, issued 1993.

———. "GrassPave2 and GravelPave2," 2006. http://www.invisiblestructures.com/wp-content/uploads/2016/05/GPGV_brochure.pdf.

Kjelgren, Roger, and Thayne Montague. "Urban Tree Transpiration over Turf and Asphalt Surfaces." *Atmospheric Environment*, Conference on the Benefits of the Urban Forest, 32, no. 1 (January 1, 1998): 35–41. doi:10.1016/S1352-2310(97)00177-5.

Konarska, Janina, Johan Uddling, Björn Holmer, Martina Lutz, Fredrik Lindberg, Håkan Pleijel, and Sofia Thorsson. "Transpiration of Urban Trees and Its Cooling Effect in a High Latitude City." *International Journal of Biometeorology* 60, no. 1 (June 6, 2015): 159–72. doi:10.1007/s00484-015-1014-x.

Kramer, Paul J. *Water Relations of Plants*. New York, N.Y: Academic Press, 1983.

LI-COR Biosciences. "LI-COR 6400." User's Manual. Lincoln, Nebraska: LI-COR, Inc., 2012. https://www.licor.com/documents/s8zyqu2vwndny903qutg.

Lindsey, Patricia, and Nina Bassuk. "Redesigning the Urban Forest from the Ground Below: A New Approach to Specifiying Adequate Soil Volumes for Street Trees." *Arboricultural Journal* 16 (1992): 25–39.

———. "Specifying Soil Volumes to Meet the Water Needs of Mature Urban Street Trees and Trees in Containers." *Journal of Arboriculture* 17, no. 6 (June 1991): 141–49.

Lindsey, Patricia, and Nina L. Bassuk. "A Nondestructive Image Analysis Technique for Estimating Whole-Tree Leaf Area." *HortTechnology* 2, no. 1 (March 1992): 66–72.

Lubell, Jessica D. "Evaluating Landscape Performance of Six Native Shrubs as Alternatives to Invasive Exotics." *Horttechnology* 23, no. 1 (February 2013): 119–25.

Lucke, T., T. Johnson, S. Beecham, D. Cameron, and G. Moore. "Using Permeable Pavements to Promote Street Tree Health, to Minimize Pavement Damage and to Reduce Stormwater Flows." Porto Alegre, Brazil, 2011.

Lupu, Oana Pohoață, and Lucia Draghia. "The Relationship between Growth Prediction and Soil Surface for Three Urban Tree Species in Romania." Draft journal article. University of Agricultural Sciences and Veterinary Medicine of Iași, Faculty of Horticulture, 3 Mihail Sadoveanu Alley, Iași, 700490, Romania, 2016.

Martine, Chris. *Extreme Weeds of Parking Lots : Plants Are Cool, Too! Episode 6*, 2015. https://www.youtube.com/watch?v=HpstofPFX0I.

Maryland-National Capital Park and Planning Commission. "Prince George's County Landscape Manual." Prince George's County, MD: Maryland-National Capital Park and Planning Commission, December 2010. http://www.pgplanning.org/Assets/Planning/Development+Review/Prince+George$!e2$!80$!99s+County+Landscape+Manual/Prince+George$!27s+County+Landscape+Manual+-+December+2010.pdf.

McCarthy, Heather R., Diane E. Pataki, and G. Darrel Jenerette. "Plant Water-Use Efficiency as a Metric of Urban Ecosystem Services." *Ecological Applications* 21, no. 8 (December 1, 2011): 3115–27. doi:10.1890/11-0048.1.

McPherson, E. G., and J. Muchnick. "Effect of Street Tree Shade on Asphalt Concrete Pavement Performance." *Journal of Architectural Education (1984-)* 31, no. 6 (November 2005): 303–10.

McPherson, E. Gregory, David J. Nowak, and Rowan Rowntree. *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project /*. Radnor, PA: Northeastern Forest Experiment Station, 1994. http://hdl.handle.net/2027/umn.31951d02995937i.

Minitab (version 2017). Windows. State College, PA: Minitab Inc., 2017.

Morgenroth, Justin, Graeme Buchan, and Bryant C. Scharenbroch. "Belowground Effects of Porous pavements—Soil Moisture and Chemical Properties." *Ecological Engineering* 51 (February 2013): 221–28. doi:10.1016/j.ecoleng.2012.12.041.

Morgenroth, Justin, Bernardo Santos, and Brad Cadwallader. "Conflicts between Landscape Trees and Lawn Maintenance Equipment – The First Look at an Urban Epidemic." *Urban Forestry & Urban Greening* 14, no. 4 (2015): 1054–58. doi:10.1016/j.ufug.2015.10.002.

Mullaney, Jennifer, Terry Lucke, and Stephen J. Trueman. "A Review of Benefits and Challenges in Growing Street Trees in Paved Urban Environments." *Landscape and Urban Planning* 134 (February 2015): 157–66. doi:10.1016/j.landurbplan.2014.10.013.

Mullaney, Jennifer, Stephen J. Trueman, Terry Lucke, and Shahla Hosseini Bai. "The Effect of Permeable Pavements with an Underlying Base Layer on the Ecophysiological Status of Urban Trees." *Urban Forestry & Urban Greening* 14, no. 3 (2015): 686–93. doi:10.1016/j.ufug.2015.06.008.

"New Brunswick, NJ." *New Jersey Weather and Climate Network*, 2016. http://www.njweather.org/station/1101.

Nowak, David J., Daniel E. Crane, and Jack C. Stevens. "Air Pollution Removal by Urban Trees and Shrubs in the United States." *Urban Forestry & Urban Greening* 4, no. 3–4 (April 3, 2006): 115–23. doi:10.1016/j.ufug.2006.01.007.

"Office of the New Jersey State Climatologist," 2017. http://climate.rutgers.edu/stateclim/?section=njcp&target=NJCnormex.

Osone, Yoko, Satoko Kawarasaki, Atsushi Ishida, Satoshi Kikuchi, Akari Shimizu, Kenichi Yazaki, Shin-ichi Aikawa, Masahiro Yamaguchi, Takeshi Izuta, and Genki I. Matsumoto. "Responses of Gas-Exchange Rates and Water Relations to Annual Fluctuations of Weather in Three Species of Urban Street Trees." *Tree Physiology* 34, no. 10 (October 1, 2014): 1056–68. doi:10.1093/treephys/tpu086.

Page, Jonathan L., Ryan J. Winston, and William F. Hunt III. "Soils beneath Suspended Pavements: An Opportunity for Stormwater Control and Treatment." *Ecological Engineering* 82 (September 2015): 40–48. doi:10.1016/j.ecoleng.2015.04.060.

Pataki, Diane E., Heather R. McCarthy, Elizaveta Litvak, and Stephanie Pincetl. "Transpiration of Urban Forests in the Los Angeles Metropolitan Area." *Ecological Applications* 21, no. 3 (April 1, 2011): 661–77. doi:10.1890/09-1717.1.

Pearcy, Robert W., E. Detlef Schulze, and Reiner Zimmermann. "Chapter 8: Measurement of Transpiration and Leaf Conductance." In *Plant Physiological Ecology*. Springer Science+Business Media B.V., 1989.

Peper, Paula J., and E. Gregory McPherson. "Evaluation of Four Methods for Estimating Leaf Area of Isolated Trees." *Urban Forestry & Urban Greening* 2, no. 1 (January 1, 2003): 19–29. doi:10.1078/1618-8667-00020.

Rainer, Thomas, and Claudia West. *Planting in a post-wild world: designing plant communities for resilient landscapes*, 2015.

Robichaud, Beryl, Karl Anderson, and Beryl Robichaud. *Plant Communities of New Jersey: A Study in Landscape Diversity*. New Brunswick, N.J: Rutgers University Press, 1994.

Roman, Lara. "How Many Trees Are Enough? Tree Death and the Urban Caonpy." *Scenario Journal* 04 (Spring 2014). https://www.fs.fed.us/nrs/pubs/jrnl/2014/nrs_2014_roman_001.pdf.

Sanders, Jessica R., and Jason C. Grabosky. "20 Years Later: Does Reduced Soil Area Change Overall Tree Growth?" *Urban Forestry & Urban Greening* 13 (2014): 295–303.

Scharenbroch, Bryant C., Justin Morgenroth, and Brian Maule. "Tree Species Suitability to Bioswales and Impact on the Urban Water Budget." *Journal of Environmental Quality* 45, no. 1 (January 2016): 199–206. doi:10.2134/jeq2015.01.0060.

Schlesinger, William H., and Brian F. Chabot. "The Use of Water and Minerals by Evergreen and Deciduous Shrubs in Okefenokee Swamp." *Botanical Gazette* 138, no. 4 (1977): 490–97.

Shashua-Bar, Limor, David Pearlmutter, and Evyatar Erell. "The Cooling Efficiency of Urban Landscape Strategies in a Hot Dry Climate." *Landscape and Urban Planning* 92, no. 3–4 (September 30, 2009): 179–86. doi:10.1016/j.landurbplan.2009.04.005.

Smiley, E. Thomas. "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement." New Orleans, LA, 2016.

Smiley, E. Thomas, Lisa Calfee, Bruce R. Fraedrich, and Emma J. Smiley. "Comparison of Structural and Noncompacted Soils for Trees Surrounded by Pavement." *Arboriculture & Urban Forestry* 32, no. 4 (2006): 164–69.

Sustainable Endowments Institute. "Green Report Card 2011-Rutgers University." *The College Sustainability Report Card*, 2011. http://www.greenreportcard.org/report-card-2011/schools/rutgers-universitynew-brunswick/surveys/campus-survey.html#climate.

Sustainable SITES. "Rating System For Sustainable Land Design and Development." Green Business Certification Inc., 2014.

Thompson, J. William, and Kim Sorvig. *Sustainable Landscape Construction: A Guide to Green Building Outdoors*. Washington, D.C: Island Press, 2000.

Thorne, Mark S., Quentin D. Skinner, Michael A. Smith, J. Daniel Rodgers, William A. Laycock, and Sule A. Cerekci. "Evaluation of a Technique for Measuring Canopy Volume of Shrubs." *Journal of Range Management* 55, no. 3 (2002): 235–41. doi:10.2307/4003129.

Urban, James. "Nursery: The Root of the Problem." *Landscape Architecture Magazine*, April 2013.

———. "Will the Trees Grow?" New Orleans, LA, 2016.

US Environmental Protection Agency. "Stormwater Phase II Rule: An Overview." Fact Sheet. US Environmental Protection Agency, rev 2005. https://www.epa.gov/sites/production/files/2015-11/documents/fact1-0.pdf.

US Forest Service. "Gleditsia Triacanthos L." Accessed March 6, 2017. https://www.na.fs.fed.us/Spfo/pubs/silvics_manual/volume_2/gleditsia/triacanthos.htm.

"USDA Plant Hardiness Zone Map." Agricultural Research Service, US Department of Agriculture., 2012. http://planthardiness.ars.usda.gov.

Viswanathan, Bhavana, Astrid Volder, W. Todd Watson, and Jacqueline A. Aitkenhead-Peterson. "Impervious and Pervious Pavements Increase Soil CO_2 Concentrations and Reduce Root Production of American Sweetgum (Liquidambar Styraciflua)." *Urban Forestry & Urban Greening* 10, no. 2 (2011): 133–39. doi:10.1016/j.ufug.2011.01.001.

Volder, Astrid, Todd Watson, and Bhavana Viswanathan. "Potential Use of Pervious Concrete for Maintaining Existing Mature Trees during and after Urban Development." *Urban Forestry & Urban Greening* 8, no. 4 (2009): 249–56. doi:10.1016/j.ufug.2009.08.006.

Watson, W. Todd, and Astrid Volder. "Use of Pervious Pavements to Preserve Urban Forests and Urban Watersheds." Texas A&M University, 2007.

Xiao, Qingfu, and E. Gregory McPherson. "Performance of Engineered Soil and Trees in a Parking Lot Bioswale." *Urban Water Journal* 8, no. 4 (August 1, 2011): 241–53. doi:10.1080/1573062X.2011.596213.

Zhao, Chang, and Heather A. Sander. "Quantifying and Mapping the Supply of and Demand for Carbon Storage and Sequestration Service from Urban Trees." *PLoS ONE* 10, no. 8 (August 28, 2015): 1–31. doi:10.1371/journal.pone.0136392.

Zoppo, Avalon. "Rutgers Rakes in Nearly $5 Million from Parking Violations." *My Central Jersey*, August 7, 2016. http://www.mycentraljersey.com/story/news/education/college/rutgers/2016/08/07/rutgers-rakes-nearly-5-million-parking-violations/88009580/.