Using a Novel Research Framework to Assess Water Quality Impacts of Urban Trees

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ABSTRACT

In 2016, the Chesapeake Bay Program Expert Panel to Define Best Management Practice (BMP) Effectiveness for Urban Tree Canopy Expansion found that stormwater runoff reduction due to tree canopy size and species make-up could be quantified in terms of inches of water retained and runoff intensity (Law and Hanson, 2016). The Expert Panel recommended an urban tree canopy BMP credit for tree planting, and also recommended considering a new BMP to credit conservation and maintenance of the existing tree canopy in urban areas. The research described in this report sought to understand how urban trees reduce stormwater runoff in different settings, with a focus on two primary hypotheses:

H1: *Urban Forest characteristics that influence ecohydrology occur in common configurations and these configurations can be captured through the development of an urban forest typology.*

H2: *More complex urban forest types (e.g., those having more canopy layers, greater density, more understory plants or shrubs, litter layers, etc.) will result in greater runoff volume reduction.*

In answering the first hypothesis, research focused on deriving a list of characteristics that could be used to categorize trees into different typologies. The result was a list of fourteen "target" and 12 "reserve" tree setting characteristics that could be derived form geospatial data. Data were then assembled for Montgomery County, and analyses were conducted in test locations to both identify and characterize individual trees using automated methods. The results suggest that it is possible to develop Ecohydrological Typology for urban trees, based solely on remotely sensed geospatial data. The results are encouraging and work is ongoing at the University of British Columbia to continue to develop the typology.

The second hypothesis was investigated using a combination of monitoring and modeling using data from four monitoring sites at two locations. The Maryland School for the Blind in Baltimore, MD, which had two plots of trees with Closed Canopy, and the Asbury Methodist Village retirement community in Gaithersburg (Montgomery County), Maryland with one plot of Single Trees and one of an Open Canopy Cluster. The sites were monitored in 2018, including measures of sap flow (a surrogate for transpiration), soil moisture in the first 30 cm of soil, and weather data including rainfall both under the tree canopy and in the open, relative humidity, and temperature. These data were used to evaluate how trees in different settings affected elements of the water balance, including transpiration, interception, infiltration and runoff.

Sap flow acts as a surrogate for transpiration, or tree water use, and was measured continuously between April of 2018 and November of 2019 at both locations. The resulting data suggest that sap flux is heavily influenced by Vapor Pressure Deficit (VPD); VPD is influenced by atmospheric conditions, and especially the temperature and humidity. As expected, dry and hot conditions corresponded with greater amounts of transpiration. In addition, it appeared that Single Trees had greater transpiration on a per-tree basis than Closed Canopy trees, with trees in a cluster but with Open Canopy having rates in between the other two groups. This result reflects the greater access of these single trees to sunlight and environmental elements. The study also found no relationship between soil moisture and transpiration rates. Tree species could be compared in the Closed

Canopy setting because of the presence of three species, including red maples, tulip poplars and sweet gum. When compared on a water use per DBH basis, the tulip poplars had higher peak water use, and in 2018, where monitoring did not begin until June, higher water use overall. By contrast, the red maples had higher total water in 2029 when monitoring began in April, due to earlier leaf out for this species.

Interception is the process by which trees intercept rainfall in the tree canopy. In this study, interception was measured by comparing the amount of rainfall in open areas to rainfall measured under the tree canopy for each site. The results suggested that trees in all settings were able to intercept rainfall, at rates of approximately 22% during the growing season and 10% outside of the growing season. These results are in the range of findings from other studies.

Infiltration and runoff were evaluated using a combination of measured and estimated values, including Throughfall (rainfall measured under the tree canopy), Soil Moisture and spreadsheets that used the Green and Ampt Infiltration model to estimate surface runoff. Although soil texture and bulk density was measured at each site, with the goal of using these data to estimate a single Saturated Hydraulic Conductivity value (k) for each location, the approach was modified so that the k value was used as a calibration parameter to match the observed to predicted soil moisture for each storm event. The results from storm events measured over the observed time period suggest that runoff coefficients are highest in the Single Tree setting, lowest in the Closed Canopy setting, and in between in the Open Canopy Cluster. However, these results were not significantly different.

Comparisons of the results with other models and the Chesapeake Bay Program Urban Tree Canopy Expansion credit suggests that: 1) The runoff coefficients (and curve numbers) observed are highly variable but in the range of other methodologies; 2) the estimated phosphorus loads for the Single and Closed Canopy settings are lower than the Tree Canopy over Turf Grass values from the Chesapeake Bay CAST model, but higher than True Forest.

Taken together, the results of this study suggest that trees do perform differently in each setting, and that it is possible to use remotely sensed data to group urban trees using an Ecohydrological Typology. Work is ongoing at the University of British Columbia to refine the Typology using data from Montgomery County, and at the University of Maryland to evaluate the transpiration data on a per-area (e.g., per hectare) basis. The results also suggest that the methodologies used in the study were effective measure of urban tree performance with some potential modifications or enhancements to the study design.

Future recommended hypotheses could focus to a greater extent on the impacts of trees on urban soils, potentially by measuring soil moisture at greater depths in the soil profile. In addition, the study was able to measure the amount of runoff, but could not quantify the amount of runoff reduction without soil moisture probes in a turf-only setting. Finally, the three settings offered a good cross-section of urban forest types, but none of the three settings had an extensive under-story and the soil had similar levels of organic matter in all three settings. In future studies, it would be interesting to investigate a forest patch with a more complex understory and soil structure.

Recommended future hypotheses include:

1. Do urban trees draw transpiration from the deep soil profile during drier periods, such that the water balance should account for this additional input? Are we able to develop a statistical model based on transpiration, soil moisture and environmental conditions that predicts soil moisture?

2. How are urban soils impacted by trees in the urban environment, and do current models adequately capture these impacts?
3. Is runoff depth from turf different than runoff from urban trees in various settings for storm events of similar depth, intensity and soil moisture conditions?
4. Do "high quality" forest patches, with management to improve the understory, soil conditions and complexity perform better than closed canopy forest patches of lower quality?
5. Can the steps used to develop an Ecohydrological Typology completed in this study be employed to classify trees in Montgomery County into distinct typologies and to create county-wide extracted datasets?

1 INTRODUCTION AND BACKGROUND

In 2016, the Chesapeake Bay Program Expert Panel to Define Best Management Practice (BMP) Effectiveness for Urban Tree Canopy Expansion found that stormwater runoff reduction due to tree canopy size and species make-up could be quantified in terms of inches of water retained and runoff intensity (Law and Hanson, 2016). The Expert Panel recommended an urban tree canopy BMP credit for tree planting, and also recommended considering a new BMP to credit conservation and maintenance of the existing tree canopy in urban areas. They foresaw a need for research to evaluate the effect of the tree canopy of non-forested lands on water quality, continued research on the effect of soils on tree canopy growth in urban watersheds, and collection of multi-year field data that explicitly measure nutrient fluxes associated with areas of tree canopy. The research described in this report sought to understand how urban trees reduce stormwater runoff in different settings through a combination of literature review, field monitoring and spatial analysis of remotely sensed and other data. The research will be helpful to understand tree impacts on soil moisture, and how tree setting (i.e., cluster versus single trees versus closed canopy) impacts the water balance.

1.1 Urban Tree Stormwater Function

As a part of a 2016 literature synthesis, the Center for Watershed Protection reported considerable variability in how urban tree benefits are calculated (CWP, 2016). Consequently, methods to assign credits to urban trees are variable both in how those benefits are quantified and the value of the credit itself (Stone Environmental, Inc. 2014). The underlying commonality in all of the crediting approaches, however, is that runoff reduction is used as a basis for crediting. Thus, the primary impact on water quality is attributed to the runoff reduction provided by trees. Trees provide runoff reduction through interception in the tree canopy, evapotranspiration, and enhanced soil infiltration (Figure 1).

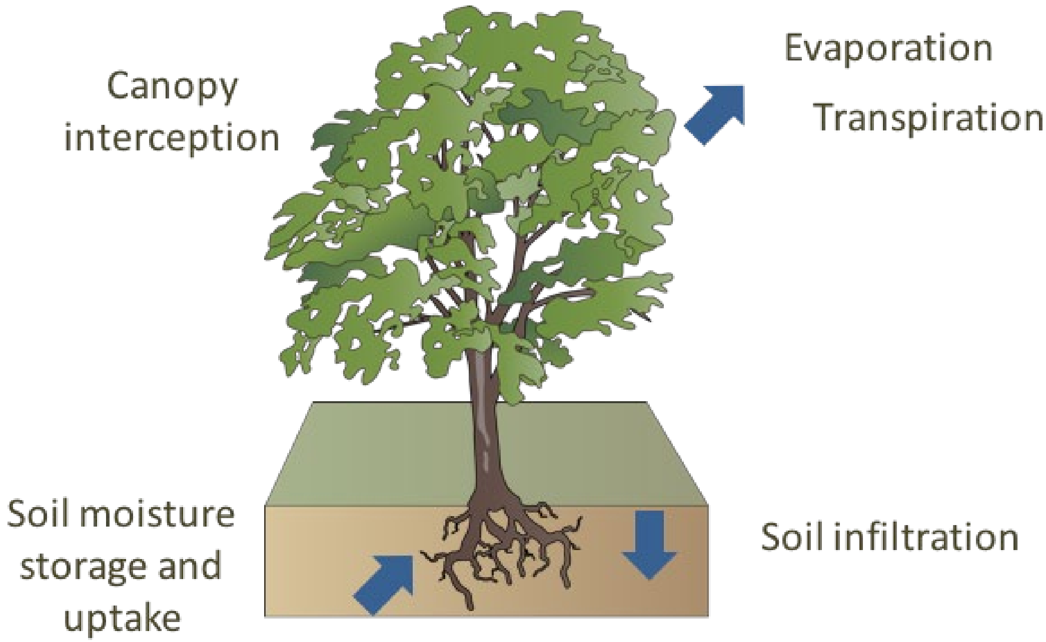


Figure 1. Ecohydrological functions that reduce stormwater runoff. (Image courtesy of the Integration and Application Network, UMD Center for Environmental Science)

1.1.1 INTERCEPTION AND EVAPOTRANSPIRATION

Interception and evapotranspiration (ET) are the two key processes by which trees use or lose water (Nisbet, 2005) and thus these processes have a significant effect on the volume of runoff generated below tree canopies. A compilation of studies on urban forests found a wide range of annual interception from 6% - 66% (Law et al., 2016), with greater values for evergreen species compared to deciduous species. For example, interception may be as high as 66.5% for evergreen trees as documented by Xiao et al. (1998) on the West Coast or 15% for pear tree or 27% for an evergreen oak (Xiao et al., 2000). Modeling estimates for interception in the Mid-Atlantic range from 14.5% to 19.6% (Band et al., 2010). The variability of canopy interception is a function of leaf area index and tree structure but is also dependent on the meteorological events (Crockford and Richardson, 2000). However, Nisbet (2005) found that the annual interception is constant given a range in total annual precipitation but differs significantly for conifer and broadleaf species shown in Figure 2.

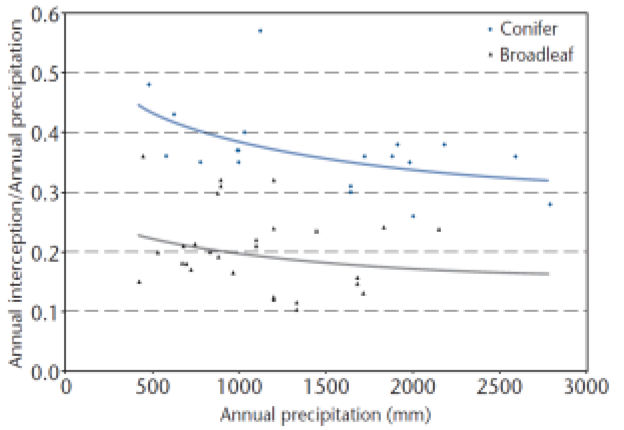


Figure 2. Comparison of interception for conifer and broadleaf species (Nesbit, 2005)

Modeling work by Band et al. (2010) concluded that tree canopy ET influences runoff production through removal of soil water that in turn increases soil pore space available for infiltration. In urban areas, trees may transpire from 0.2 to 46.7 gallons per tree per day influenced by seasonality, species, and rainfall conditions, where trees regulate transpiration losses based on climatic conditions through the stomata (Law et al., 2016). Despite the wide range in total amount of water transpired by urban trees, the ET rate for urban trees is comparable to natural forests (Table 1).

Table 1. Comparison of transpiration rates for urban trees and natural forests during the growing season (as summarized in Law and Hanson, 2016).

Urban trees	Natural Forests
0.1 – 2.49 mm/d	0.5 – 3.0 mm/d

The measured or modelled runoff reduction attributed to urban trees is also highly variable due to the scale of analyses. Watershed scale studies typically evaluate the effect of trees as a percentage of canopy cover within the watershed measured by acres or even square miles. By contrast, stormwater management BMPs are typically evaluated in smaller, plot-scale studies with and without trees and measured in square feet or fractions of acres. For example, Wang et al. (2008) found enhanced runoff reduction when tree cover increased from 12 to 50% in a watershed, while Page et al. (2014) measured an 80% runoff reduction at a plot-scale. Again, the range in runoff reduction, while highly variable in urban areas, are comparable with ranges reported for natural forests, 2.6% to 88.8% and 8% to 80%, respectively (Law and Hanson, 2016).

Despite the extensive research on specific processes contributing to volume reduction, the water quality benefits are less well characterized. In the national literature search completed by CWP (2016) only one of nine studies provided data to directly compare the water quality effects of urban trees (Denman, 2006). Three other studies combined the effects of soil media and trees with control plots (Denman et al., 2011, 2015; Read et al., 2008). Denman (2006) estimated an 82% to 95% total nitrogen reduction for a street tree bioretention compared to -7% to 36% reduction by their unplanted controls. In contrast, Roseen et al. (2009) found higher phosphorus loads from sites with street trees. Other contributions from the urban forest that may contribute to improved water quality include the trapping of atmospheric particles and uptake of atmospheric nitrogen.

1.1.2 INFILTRATION

Infiltration also affects the amount of runoff generated, and the amount of infiltration is a function of pore space available in the soil, and other soil characteristics. Trees impact the storage capacity available in the soil through the process of transpiration, which removes water from the soil profile. In addition, tree root mass and leaf litter affect soil structure, enhancing the infiltration potential. As roots grow, they create preferential flow paths, promoting more rapid movement of water through the soil, even when soils are compacted (Bartens et al. 2008). Thus, trees can promote greater soil moisture in some instances by facilitating water movement into the soil (Day et al. 2010). In addition to enhancing infiltration, this increased soil moisture suggests an increased opportunity for biological processes in the soil, nutrient utilization and potential for denitrification in soils within the root zone (Law et al., 2016). However, enhanced infiltration may also result in deeper infiltration and drier surface soils, consequently reducing the potential for surface runoff. The addition of organic matter to the soil through leaf litter also increases carbon content, potentially increasing soil nutrient uptake and cycling and infiltration rate (Day et al., 2010; Saxton and Rawls, 2006).

1.2 Current Stormwater Credits and Modeling of Urban Trees

Increasingly, states and municipalities credit trees for stormwater management and runoff reduction, but they vary in their approach. Literature reviews completed by CWP provide a summary of current stormwater crediting approaches and the effects of trees on stormwater runoff and urban trees (Table 2; adapted from Law and Hanson, 2016, Appendix C).

Table 2. Summary of Tree Stormwater Crediting

Authority	Year Enacted / Revised	Type of Credit	Distance from Impervious Surface	Credit Details	References
State of NY	2015	Impervious Area Reduction	New = 10′ max Existing = 20′ max	New trees = 100 sf of connected Impervious Cover (IC) (must be ≥2" caliper OR ≥6' tall for evergreens) Existing trees = connected IC equivalent to ½ the canopy area (must be ≥4" caliper) Max of 25% of connected ground-level IC can be credited by trees.	NY SWMM 2015, Section 5.3.4
Washington, D.C.	2013	Volume Reduction	Not specified	New trees = 10 ft^3 / tree (must be ≥1.5" caliper) Existing trees = 20 ft^3 / tree For credit, tree type must have average mature spread of ≥35'.	DDOE SWMG 2020, Section 3.14
State of PA	2006	Volume Reduction	New = n/a Existing = 100′ max	New trees, evergreen = 10 ft^3 / tree (must be ≥6' tall) New trees, deciduous = 6 ft^3 / tree (must be ≥2" caliper) Existing trees, within 100′ of IC: (must be ≥4" caliper) Volume reduction = 0.5″ x Canopy Area Existing trees, within 20′ of IC: (must be ≥4" caliper) Volume reduction = 1″ x Canopy Area Max of 25% of the runoff volume can be credited by trees.	PA SW BMP Manual 2006, BMP 5.6.3 and Ch. 8, p. 23/46
State of VT	2016	Volume Reduction	Not specified	Single trees = 5 ft^3 / tree (must be ≥2" caliper OR ≥6' tall for evergreens) Reforestation (minimum 2500 sf area & 25′ wide): *Active* reforestation: Volume reduction = 0.1″ x Reforested Area *Passive* reforestation:	VT SWM Manual 2016, Section 4.2.1

Authority	**Year Enacted / Revised**	**Type of Credit**	**Distance from Impervious Surface**	**Credit Details**	**References**
				Volume reduction = 0.05" x Reforested Area	
EPA Chesapeake Bay Program	2016	Land Use Change to Forest	N/A	Forest land use - credit based on conversion from different existing land use load rates 100 trees / 1 acre (minimum 0.25 acres to aggregate) >2" DBH for at least half the trees	CBP Expert Panel report
Urban Tree Canopy Expansion	2016	Land Use Change	None specified or over impervious	Credit is equal to approximately 144 ft^2/tree planted. Same credit regardless of species, and trees are classified into "Tree Canopy over Impervious" or "Tree Canopy Over Turfgrass"	CBP Expert Panel report
Pine Lake, GA	2003	Volume Reduction	None specified	Trees < 12" caliper= 10 gallons/caliper inch (or 1.34 ft^3/in) Trees > 12" caliper = 20 gallons/caliper inch (or 2.67 ft^3/in)	City of Pine Lake Building Code, Section 18-5 (b)(6)
Portland, OR	2016	Impervious Area Reduction	New = 10' max Existing = 25' max	New trees, evergreen = 200 sf / tree (must be ≥5' tall) New trees, deciduous = 100 sf / tree (must be ≥1.5" caliper) Existing trees, 1.5 – 6" caliper = 200 sf Existing trees, >6" = 400 sf *per 6" of caliper* For sites with > 1,000 sf of IC, no more than 10% can be credited by trees.	City of Portland SWM Manual 2016, Section 2.3.4.3
Sacramento, CA	2007	Impervious Area Reduction	25' max	New trees, evergreen = 200 sf / tree New trees, deciduous = 100 sf / tree Existing trees = ½ the canopy area	Stormwater Quality Design Manual 2007, pg. 221 & Section INT-1, pg 89
Indianapolis, IN	2016	Impervious Area Reduction	New = 10' max	New trees = 100 sf of connected IC (must be ≥2" caliper OR ≥6' tall for evergreens) Existing trees = credit allowed, but not explained Max of 25% of IC on site can be credited by trees.	City of Indianapolis Green Infrastructure Supplemental Document 2016, Section 3.3

Authority	Year Enacted / Revised	Type of Credit	Distance from Impervious Surface	Credit Details	References
Seattle, WA	2016	Impervious Area Reduction	New = 10’ max Existing = 20’ max	New trees, evergreen = 50 sf / tree (must be ≥4' tall) New trees, deciduous = 20 sf / tree (must be ≥1.5” caliper) Existing trees, evergreen = 20% of canopy area (must be ≥4” caliper) Existing trees, deciduous = 10% of canopy area (must be ≥4” caliper) Max of 25% of IC on site can be credited by trees.	City of Seattle SW Manual 2016, Section 5.2
Philadelphia, PA	2020	Impervious Area Reduction	New = 10’ max	New trees = 100 sf / tree (must be ≥2" caliper OR ≥6' tall for evergreens) Existing trees = only the IC under canopy (must be ≥4” caliper and overlapping canopy cannot be double-counted) Max of 25% of connected ground-level IC can be credited by trees.	Philadelphia Water Stormwater Management Guidance Manual (v3.0), Section 3.1.5 “Tree Disconnection Credit”

1.2.1 STORMWATER REGULATION AND TREE CREDITING IN MONTGOMERY COUNTY

Stormwater is regulated in Montgomery County using the Maryland Stormwater Management Design Manual standards. Although individual trees do not receive stormwater credit, preserving natural forest areas allows the designer to subtract the preserved area from the total site area. This calculation contributes to achieving the Environmental Site Design (ESD) credit, which can be applied to stormwater treatment requirements throughout the state. In addition, the Chesapeake Bay Program tree credits, both for Urban Tree Canopy Expansion (i.e., individual tree planting) and Urban Forestry (trees planted as a part of an approved planting plan.

None of the current tree credits in Montgomery County consider tree size or species. While the CBP credit does not explicitly reward protection of existing forests, the Maryland Stormwater manual by contrast does not award credits for new tree planting. Further, the management context outside of a distinction between "forest" and "individual tree" is not considered in awarding these credits, with the exception of the distinction between "Trees over Impervious" and "Trees Over Turf" in the CBP Credit.

1.2.2 STORMWATER MODELS AND CALCULATORS

In addition to credits provided by local or state governments or other agencies, trees have been incorporated into tools and credits using a few different assumptions. Most stormwater runoff models have some method to incorporate the hydrologic impact of trees, with methods ranging from treating trees as a storage BMP to accounting for interception only (CWP, 2018). Two models that explicitly account for the impacts of the tree canopy include i-Tree Hydro (Wang and Endreny, 2008; https://www.itreetools.org/tools/hydro) and the water balance model used to develop the CBP tree canopy credits. This water balance model was later updated to account for curve number adjustments based on soil water storage (Hynicka and Caraco, 2017). While both models account for interception, ET and runoff processes, there are some differences in their approaches. The Water Balance Model was designed explicitly to evaluate individual trees, i-Tree Hydro is flexible in the scale, and can be calibrated to watershed-scale hydrology. Another difference is the methods that each uses to calculate runoff depths. While the Water Balance Model relies on NRCS Curve number methodologies and daily rainfall data, using a curve number adjustment to reflect the impact of trees on underlying soils, i-Tree Hydro is a more mechanistic model, and uses infiltration models to predict soil infiltration over the course of a storm.

1.3 Urban Tree Typology

Given the influence of trees on runoff production and the inextricable link between runoff and water quality, the evaluation of urban tree impacts on water quality must consider the more complex system of the environment in which the tree grows, rather than just the individual tree. Typologies allow us to classify these systems to better understand their influence on ecosystem function, rather than trying to understand every element of the system and their interactions. Typologies have been developed to classify green infrastructure and spaces. For example, Caynes, et al. (2016) classified urban parks in Brisbane, Australia by their vegetation structure. This classification allowed them to provide a functional description of urban parks. Neuenschwander, et al. (2014) developed a green space typology, but the types were solely based on location ("private garden", "public green space") and were not based on physical characteristics. At the other end of the spectrum, tree-based typologies have been developed, but at a much more limited scale. For example, Sanders, et al.

(2013) classified planting spaces and determined the maximum size expectations of each tree within the particular groupings (such as tree pits, planting strips, unlimited soil). A typology focused on stormwater benefits classifies trees according to their immediate environmental context, thus integrating factors that influence stormwater benefits.

A "tree-based" typology, which would allow planners to understand the characteristics of each tree (e.g., its height and species), along with information about its surroundings. For example, one system may be "street trees," while another may be "single trees over turf" (**Figure 3**). Since urban stormwater management is often conducted at the parcel scale, this approach would allow for a planner to better characterize the parcel, which may have trees belonging to multiple typologies.

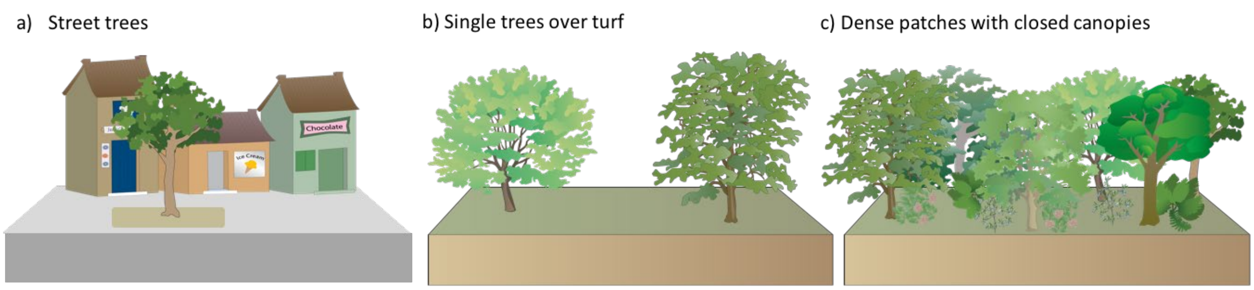


Figure 3. Examples of different urban tree typologies. (Images courtesy of the Integration and Application Network, UMD Center for Environmental Science)

Finally, another important need is the ability to characterize trees based on available GIS data (e.g., LiDAR). The increasing availability of geospatial data, combined with the high cost of collecting ground-based data. Since collecting data about every tree within a jurisdiction would be cost-prohibitive, methods that focus on remote sensing are increasingly useful to urban planners and resource managers.

2 PROJECT OBJECTIVES AND HYPOTHESES

This project's objectives were to better define urban tree and forest water balance components to test stormwater runoff reduction hypotheses. It also sought to further understand whether tree species characteristics affect runoff reduction in the urban forests. Finally, the project created new hypotheses for future research about how urban forest ecohydrological types influence runoff reduction.

H1: *Urban forest characteristics that influence ecohydrology occur in common configurations and these configurations can be captured through the development of an urban forest typology.*

H2: *More complex urban forest types (e.g., those having more canopy layers, greater density, more understory plants or shrubs, litter layers, etc.) will result in greater runoff volume reduction.*

H2-1: Trees in the closed canopy type will have greater rates of runoff and amount of sap flow (transpiration) than trees located over turfgrass.

H2-2: Red maple will have a lower rate of transpiration compared to tulip poplar but will have greater amounts of overall transpiration and a resultant stronger effect on runoff reduction.

H2-3: The greater amount of transpiration will result in larger reductions in annual runoff volume.

3 STUDY SITES

The field research component of this project used two sites: the Maryland School for the Blind, located in Baltimore, MD an Asbury Methodist Village in the City of Gaithersburg, MD (Figures 4 and 5). Two patches of trees were monitored at each site, representing different tree typologies. Asbury Methodist Village had representatives of the "Single Trees over Turfgrass" and "Cluster of Trees over Turfgrass," the Baltimore City site included two patches of trees over closed Canopy. The overall characteristics of each site, including tree species monitored for ET, soils characterization, and other site characteristics are summarized in Table 3.

Two forest patches for the closed canopy type selected for this study included two easement forest patches on the Maryland School for the Blind campus. At these sites, there are greater than 30 individual tulip poplar and red maple. Each species comprises 13-26% of the observed sites in each forest patch. Sweet gum is also very abundant in one of the forest patches and comprises 16% of the tree diversity. The two other locations for this study were located at Asbury Methodist Village, a retirement community in Gaithersburg, Maryland. Five red maple and five sweet gum trees were measured from a cluster of trees over turfgrass. These trees were planted at the same time and were about the same size and age with overlapping canopies. However, for all trees the majority of their canopies had access to sunlight (i.e., there are no understory trees). The second site at Asbury Methodist Village along Fellowship Circle included five single red maple trees over turfgrass with irrigation. These trees were approximately 40 to 50 feet apart. Since this distance exceeded canopy width, it was assumed that their roots did not interact. Both locations were relatively flat.

The trees in the two closed canopy forest patches at Maryland School for the Blind vary in size (e.g., DBH, canopy cover, and leaf area index), and were characterized and accounted for as described in the next few paragraphs. Some of the sampled trees were understory trees, while others reached the top of the canopy. This was noted and assessed for its impact on the rate and amount of transpiration and runoff production. The trees at the two locations at Asbury Methodist Village were characterized for DBH, canopy cover, and leaf area index, as well, even though they were all approximately the same size (~18.5 cm DBH). None were understory individuals.

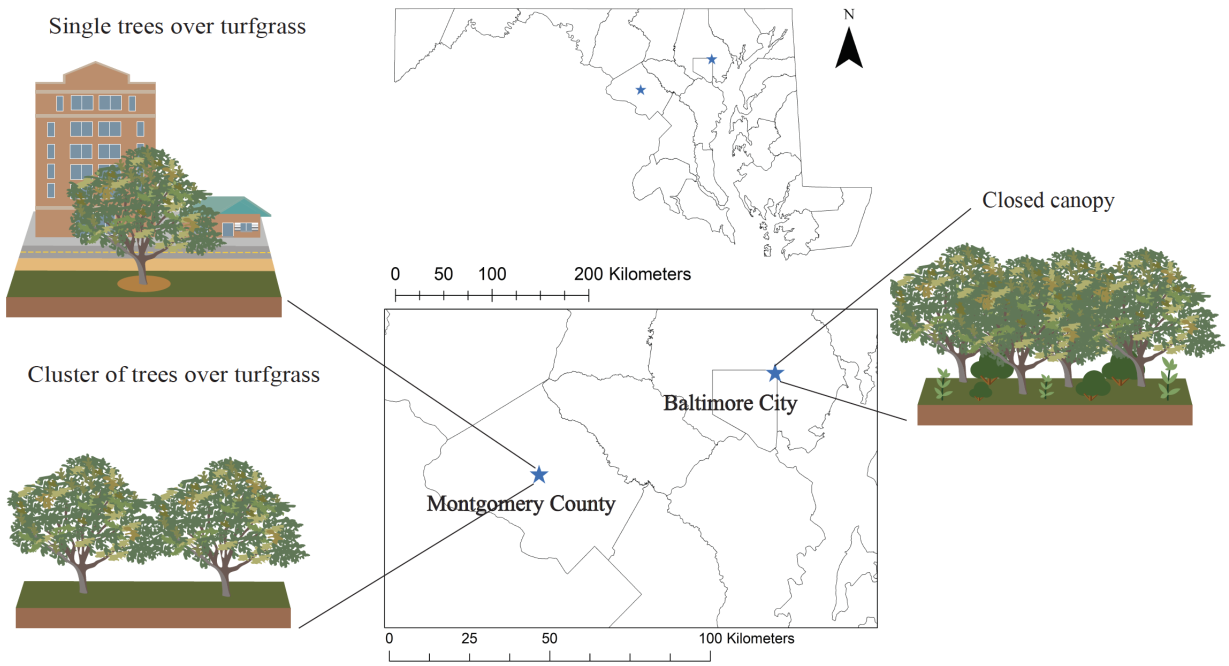


Figure 4. . Study site locations in the State of Maryland, USA. Illustrations represent the management contexts in each site. (Ponte, S., et.al. 2021)

Figure 5. Site Photos

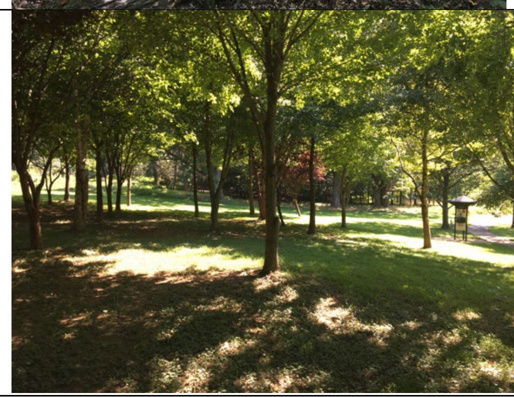
MD School for the Blind Closed Canopy Forest Patches		
Asbury Methodist Village Tree Cluster over Turfgrass		
Asbury Methodist Village Single Trees over Turfgrass and Mulch		

Table 3. Summary of Study Site Characteristics

Site	**MD School for the Blind, Baltimore County: Northwest Forest Patch**	**MD School for the Blind, Baltimore County: Southeast Forest Patch**	**Asbury Methodist Village, Montgomery County**	**Asbury Methodist Village, Montgomery County**
Tree type and numbers	Closed canopy 5 tulip poplar 5 red maple 5 sweet gum	Closed canopy 5 tulip poplar 5 red maple	Cluster over turfgrass 5 red maple 5 sweet gum	Single tree over turfgrass 5 red maple
Understory	Some smaller trees and common shrubs such as Northern spice bush	Some smaller trees and common shrubs such as Northern spice bush	None	None
Groundcover	Leaf litter, plant debris, common vegetation such as Virginia creeper	Leaf litter, plant debris, common vegetation such as English Ivy	Turfgrass	Turfgrass, mulch Note: Some Canopy over impervious cover
Soils Description	Loam-Clay Loam	Loam	Loam	Loam
Soil Organic Matter (%)	4.6	2.6	2.7	2.0
Median Soil Bulk Density (g/cc)	1.32	1.19	1.23	1.31

3.1 Tree Species Monitored

Three species of trees were monitored for sap flow (transpiration) as a part of this study: Tulip poplar, red maple and sweet gum. All three of these trees are common to urban landscaping and native forests throughout Maryland and the Chesapeake Bay watershed. The diffuse-porous xylem hydraulic architecture is characteristic of these species, meaning that the measurement methods proposed for the research could more accurately measure their sap flow. It is more challenging to accurately assess sap flow in the ring-porous xylem architectures such as are characteristic of oak species, for example.

Tulip poplars, red maples and sweet gum differ in other traits that may potentially affect runoff reduction volumes, and consequent nutrient and sediment reductions. For instance, red maples have relatively shallow roots and therefore may have limited access to deeper water in the soil. Red maples bloom earlier than tulip poplar and will have a larger annual transpiration window. They are also more tolerant of both very dry and wet conditions. Consequently, these types of traits may affect how each species influences the water balance model and thereby reduces runoff.

While the "Closed Canopy" setting included all three species, only the red maple was present in all three typologies. In addition to a slightly different tree composition, the trees in the "Closed Canopy" at the Maryland School for the Blind setting tended to be larger when compared to the same species at Asbury Village (Table 4).

Table 4. Characteristics of study trees. Values are mean ± SE.

Management Context	Tree Species	n	DBH (cm)	Height (m)	Canopy Width N-S (m)	Canopy Width E-W (m)
Single trees	*Acer rubrum* L.	5	22.4 ± 2.4	8.2 ± 0.3	8.2 ± 0.8	8.7 ± 0.7
Cluster of trees	*Acer rubrum* L.	5	24 ± 1.0	12.8 ± 0.4	9.7 ± 0.5	9.4 ± 0.4
Cluster of trees	*Liquidambar styraciflua* L.	5	30.2 ± 1.4	14.7 ± 0.8	9.2 ± 0.5	9.4 ± 0.8
Closed canopy	*Acer rubrum* L.	10	35.0 ± 4.0	20.9 ± 1.7	9.7 ± 0.9	9.0 ± 0.9
Closed canopy	*Liriodendron tulipifera* L.	11	54.1 ± 5.6	33.9 ± 1.4	9.5 ± 0.9	10.3 ± 1.2
Closed canopy	*Liquidambar styraciflua* L.	5	35.7 ± 6.8	29.1 ± 4.8	7.9 ± 1.2	8.7 ± 0.9

3.2 Site Soil Characteristics

With the exception of the Northwest patch at the Maryland School for the Blind (which was classified as a Loam-Clay Loam, and had 4.6% Organic Matter), the other sites were nearly identical in being classified as Loam, with between 2.0-2.7% Organic Matter. All four sites had a similar measured bulk density, between 1.19 and 1.32 g/cc. The Northwest patch at the Maryland School for the Blind was found to be saturated frequently during the study. Although this patch could still be used to characterize Interception and transpiration, the frequent saturation (likely due to perched groundwater) made it impossible to compare this site to others for runoff or infiltration.

4 METHODS

4.1 Field Measurements and Instrumentation

4.1.1 TRANSPIRATION

Thermal dissipation Granier sensors were inserted radially, 2 cm into the sapwood of the trees at diameter breast height (1.4 m; Figure 6). Each sensor consisted of two thermocouple cylindrical probes approximately 15 cm apart. Sensors were attached to double-shielded cable wires and connected to a CR 1000 datalogger with peripheral AM 416 or AM 16/32B multiplexers. Steps were taken to shield the sensors so that they were not influenced by ambient temperatures or rainfall.

Transpiration was estimated using data from the Granier Probes The upper probe included a heating element to increase the sap temperature. Thermocouples produced a small voltage that varied with temperature and the pair of thermocouples was used to measure the temperature difference (ΔT; ◦C) between heated and un-heated probes. As the velocity of water movement increased, more heat near the upper probe dissipated and the ΔT declined. ΔT is therefore inversely related to sap flux as a function of the maximum temperature differential between probes when flux is zero (A.C. Oishi et.al., 2016; example in Figure 7).

Figure 6. Sapflow sensors installed at the Maryland School for the Blind

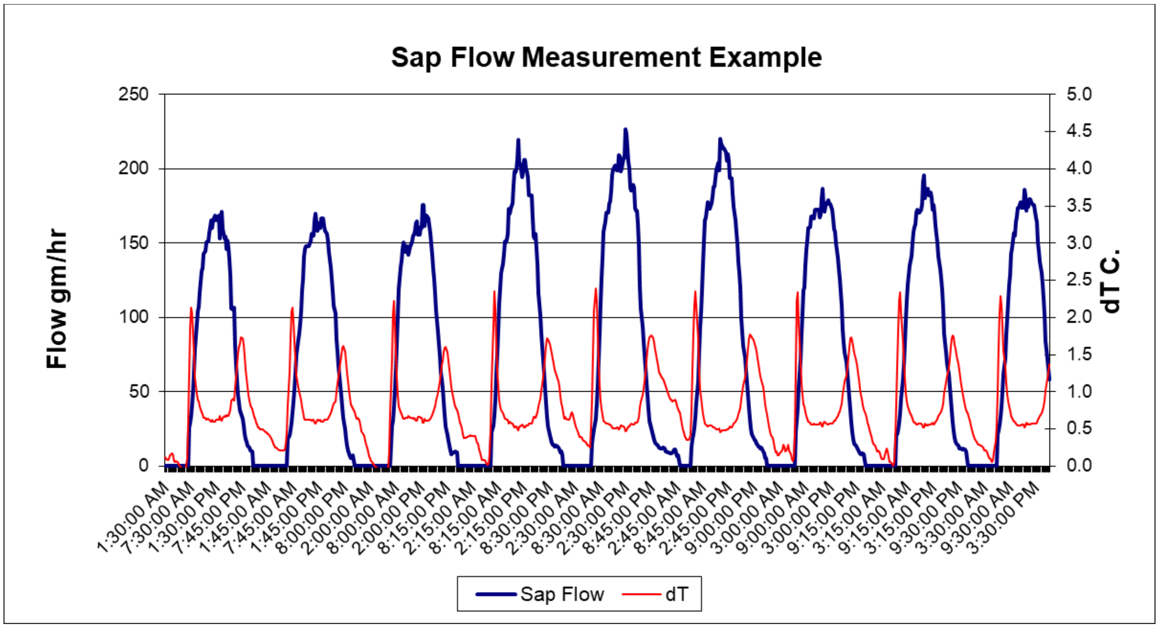


Figure 7. Sap flow Measurement Example Chart (A.C. Oishi et.al., 2016)

The temperature difference (ΔT) between the upper heated probe and the ambient temperature of the below reference probe was calculated every 30 seconds and recorded as half-hour averages. Sap flow (J_s) was calculated according to the empirical formula by Granier (1987; Equation 1):

$$J_s\ (g\ m^{-2}\ s^{-1}) = 119((\Delta T_{max} - \Delta T)/\ \Delta T)^{1.231}$$

Equation 1

where ΔT is the mean temperature difference between the sensor probes and ΔT_{max} is the temperature difference between the sensor probes under zero-flow conditions (i.e., the maximum nighttime temperature difference between the heated and unheated sensors).

4.1.2 WEATHER MEASUREMENTS

A weather station was installed in the open near field sites to characterize climate drivers of sap flow (air temperature, relative humidity, precipitation). Air temperature and relative humidity at each site was used to calculate vapor-pressure deficit (VPD). Precipitation was measured using tipping-bucket rain gauge.

4.1.3 SOIL MEASUREMENTS

In addition, soil moisture probes were installed at 30 cm depth to characterize soil moisture dynamics that the trees experience. The data were recorded at 15- or 30- minute intervals.

In addition to soil moisture, soil texture, organic matter and bulk density were measured by taking three cores at each site. Soil texture was characterized by the relative fraction (by mass) of silt, clay and sand particles in soil, and organic matter was represented as a percentage by mass.

4.2 Calculations and Estimates

4.2.1 TRANSPIRATION

Whole-tree transpiration (E) (g-H_2O/s) was estimated from the sap flux density measurements (g-H_2O/m2/s) using a predictive model from Berdanier et al., (2016). The model took into consideration the observed sap flux density, the xylem anatomy (i.e., diffuse-porous), and the radius of the tree to predict the whole tree sap flow. All species (red maple, tulip poplar, and sweetgum) monitored were diffuse-porous trees and the radius of each tree was obtained from each tree's DBH measurement. Daily total sap flux was converted from sap flux per second data.

4.2.2 VAPOR PRESSURE DEFICIT

The Vapor Pressure Deficit (VPD) is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated. Weather data, including the Relative Humidity (RH) and Temperature (T) measured at 30-minute intervals were used to calculate VPD using the method outlined by Campbell and Norman (2012; p 41).

$$VPD = a \times e^{\left([b \times T] / (T+c)\right)} \times \left(1 - \frac{RH}{100}\right)$$

Equation 2

Where:

VPD	=	Vapor Pressure Deficit (kPa)
a	=	0.611 kPa
b	=	17.502
c	=	240.97 °C
T	=	Temperature (°C)
RH	=	Relative Humidity (%)

4.2.3 RAINFALL DATA AGGREGATION AND STORM EVENT SEPARATION

The throughfall (and rainfall) measured values were recorded using a tipping-bucket rainfall gage, which recorded rainfall in 0.2 mm intervals, along with recorded times. These values were converted to storm event hyetographs by first aggregating these data into 15-minute time interval depths.

For some calculations, rainfall was divided into individual storm events. The length of time between storm events was estimated using the method described in Restrepo-Posada and Eagleson (1982). In this method, it is assumed that storm events are independent if they follow a Poisson distribution; in this distribution, the Standard Deviation of the time between events is equal to the Mean of the time between events. Using rainfall data from the Asbury Cluster site, we tried various inter-event times over the available period of record and calculated both of these statistics. After numerous iterations, we selected an inter-event time of 2 hours. Once the 2-hour inter-event time was identified, individual storm events were identified for all sites by identifying cases where rainfalls totaled at least 25 mm and were separated from other rainfall by at least 2 hours.

4.2.4 INTERCEPTION

Interception was calculated at each site by comparing the rainfall measured under the tree canopy (throughfall) to the rainfall measured in paired open areas (Equation 3). Rainfall data were aggregated to the storm-event scale to calculate interception values. In addition, some data were eliminated from consideration, including events where no throughfall was observed, and instances where throughfall exceeded precipitation in the open.

$$I = P_{Open} - P_{Throughfall}$$

Equation 3

Where:

I	=	Interception (cm)
P_{Open}	=	Precipitation measured outside of the tree canopy (cm)
$P_{Throuhfall}$	=	Precipitation measured under the tree canopy (cm)

4.2.5 SURFACE RUNOFF

Runoff volume was estimated by summing the difference between the measured throughfall rate and the estimated infiltration rate in 15-minute intervals over length of each storm event (Equation 4).

$$\mathbf{R} = \sum_{\boldsymbol{i}}(\mathbf{p_i} - \mathbf{f_i})\,\Delta\boldsymbol{t}$$

Equation 4

Where:

p_i	=	Throughfall rate (cm/hr) at time i
f_i	=	Infiltration rate (cm/hr) at time i
R	=	Runoff depth over the storm event (cm).
Δt	=	Time Step (0.25 hours)

Throughfall was directly measured through rain gage measurements collected under the canopy, which were converted into 15-minute interval data.

Potential Infiltration Rate (fp)

The potential infiltration rate for each time interval was calculated using the Green and Ampt Equation (Green and Ampt, 1911). As illustrated in Figure 8, this equation assumes that rainfall infiltrates the surface as a "wetting front", filling soil voids until the soil becomes saturated, and then moving into underlying dry soil. The potential infiltration rate is calculated based on the depth of the wetting front and soil characteristics (Equation 5).

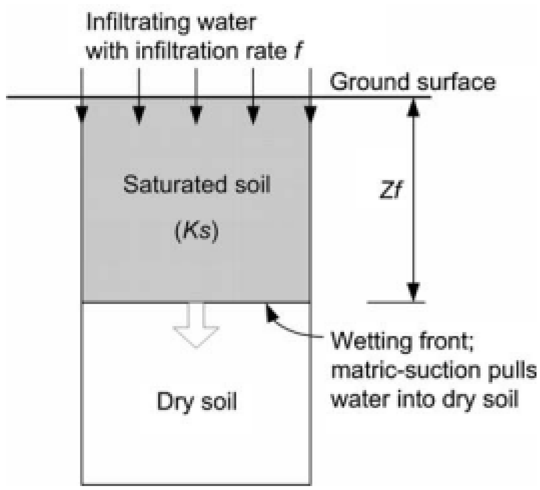


Figure 8. Wetting Front Movement Assumptions in the Green-Ampt Equation

$$f_p = K + \frac{K \times \psi(\theta_s - \theta_0)}{F}$$

Equation 5

Where:

f_p	=	Potential soil infiltration rate (cm/hr)
K	=	Soil Saturated conductivity (cm/hr)
ψ	=	Soil Suction Head (cm)
F	=	Total infiltration amount (cm)
$\theta_{s,0}$	=	Saturated and Initial Soil Moisture Content

The Suction Head (ψ) was estimated as 8.89 cm; this estimate was based on the predominant soil texture (loam), and suction head reported for loam in Rawls, Brakensiek and Miller (1983).

F, the infiltration depth, was calculated at each time step, as described below.

Saturated Moisture Content (θ_s) was estimated for each site from soil moisture probes. The soil moisture data were collected at multiple points, and an average soil moisture was chosen to reflect the conditions at a given time (t). θ_s was estimated as the maximum soil moisture recorded over the period of record for the study at each site.

Initial Soil Moisture Content (θ_0) was the average moisture content recorded at soil moisture probes at the initiation of each storm event.

The saturated conductivity (K) was used as a calibration parameter to reproduce soil moisture values observed at soil probes. This was a departure from the original intent of the project, which was to use soil characteristics combined with methodologies available from the USDA soil characteristics model (https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/drainage/?cid=stelprd b1045331) to estimate the K value. Unfortunately, using a single value for K at each location was not producing results consistent with monitored soil moisture content. As a result, this alternative approach was utilized.

Actual infiltration Rate (f)

The potential infiltration rate calculated in Equation 6 is limited by the throughfall rate, so that the actual infiltration rate (f) is determined by the following:

When $f_p < p$ $f = f_p$

When $f_p \geq p$ $f = p$

Equation 6

Infiltration Depth (F)

The infiltration depth is updated at each time step, to reflect the accumulated infiltration amount:

$$\mathbf{F_i} = \boldsymbol{F_{i-1}} + \boldsymbol{f_{i-1}}\Delta \boldsymbol{t}$$

Equation 7

Wetting Front Depth (Z)

The wetting front depth reflects the actual depth in the soil profile where the soil to which the soil infiltrated and is calculated using Equation 8. The wetting front can be important in cases where the soil profile changes with depth such as, for example, a restrictive layer or clay soil underlying a loam soil such that the saturated conductivity and saturated moisture content might vary as depth changed. In this study, soil bores suggested that the soil was relatively uniform, so the depth was not used to modify equation parameters.

$$\mathbf{Z} = \frac{\mathbf{F}}{(\boldsymbol{\theta_s} - \boldsymbol{\theta_0})}$$

Equation 8

Using Soil Moisture Data to Estimate K values

Ideally, K values are selected based on soil characteristics such as texture, organic matter content and compaction. In this study, however, we found that predicted K values based on soil characteristics produced results that were not consistent with the observed soil moisture measurements. We determined that these measurements were more reliable than an estimated K value, and consequently calibrated the K value to reflect these values.

The observed soil moisture reflected the moisture content (θ) in the first 30 cm of soil. At each 15-minute time step, we calculated the Modeled soil moisture in the first 30 using Equation 9. For a portion of the monitoring period, soil moisture was calculated in 30-minute rather than 15-minute intervals. In these cases, 15-minute intervals were interpolated as the average of the two surrounding 30-minute values. The K-value was adjusted until the modeled moisture content at the end of the storm event was very close to the observed value. When the observed value reached apparent saturation, or leveled off as in Figure 9, the K value was adjusted so that the time where the soil was saturated was similar in the observed and modeled conditions.

$$\boldsymbol{\theta} = \boldsymbol{\theta_0} + \frac{\mathbf{F}}{\mathbf{30}}$$

Equation 9

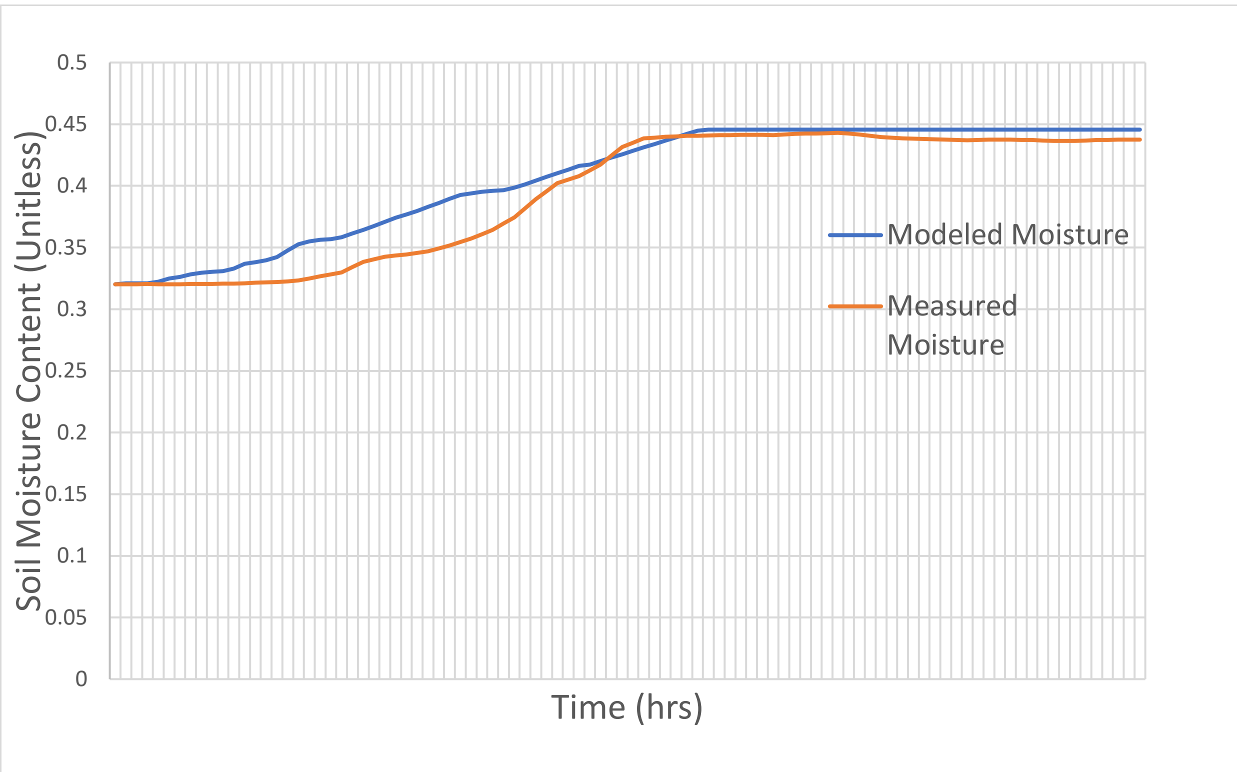


Figure 9. Modeled and Measured Moisture Over time at the "Asbury-Single" site on March 21, 2019

The initial goal was to use the soil water characteristics predictive equations provided through Soil Water Characteristics Program (Saxton and Rawls, 2006; https://hrsl.ba.ars.usda.gov/soilwater/Index.htm) to generate the initial parameters for continuous annual time series data of soil moisture conditions at each study plot. However, the runoff model did not run effectively using a single soil-characteristic derived estimate of saturated conductivity. Consequently, this parameter was used as a calibration parameter for each spreadsheet.

4.2.6 CURVE NUMBERS

Curve numbers were "back calculated" from the NRCS Curve number method, as adapted by Woodward et al. (2003). The resulting equations (Equation 10 and Equation 11) were used to estimate the curve number for each storm based on the rainfall depth and runoff depth. This analysis was restricted to storm events of least 2.5 cm.

$$\boldsymbol{CN = \frac{1000}{S + 10}}$$

Equation 10

Where:

CN	=	Curve Number
S	=	Storage Parameter

$$\boldsymbol{S = \frac{-b - \sqrt[2]{b^2 - 4 \times a \times c}}{2 \times a}}$$

Equation 11

$$\boldsymbol{b = -0.1 \times Ti - 0.95 \times Ri}$$

Equation 12

$$\boldsymbol{c = Ti^2 + Ti \times Ri}$$

Equation 13

Where:

a,b,c	=	Quadratic Equation Parameters
a	=	0.0025
Ti	=	Throughfall in inches
Ri	=	Runoff in inches

4.2.7 WEIGHTED ANNUAL RUNOFF COEFFICIENTS AND ESTIMATED LOADS

The runoff data calculated using spreadsheet models was somewhat biased in that large storms preferentially produced runoff, or were able to be modeled. However, it was desirable to compare annual estimated loads to values from the CAST model. These estimates were completed for the Single and Closed canopy types because few storm events in the "low" category for the Cluster category made it impossible to estimate annual runoff depths for this canopy type.

Annual Runoff estimates were made for the Single using the following process:

1) Rainfall data from Washington National Airport was downloaded, and daily rainfall was assembled for the period from January 1 2000 to December 31, 2019.
2) The data were categorized into depths as follows: "very low" for rainfall depths 1 cm and lower; "low" for depths between 1 and 2.5 cm; "medium" for depths between 2.5 and 5 cm; and "high" for events larger than 5 cm.
3) The fraction of rainfall falling in each category was estimated for each rainfall category.
4) It was assumed that rainfall depths <1 cm did not produce runoff under any tree canopy.
5) For each rainfall depth category/canopy type combination, an estimate runoff coefficient was estimated from model results as the total runoff depth in modeled events divided by the total rainfall for this category.
6) A weighted Rv was estimated by combining the weights derived from National Airport rainfall data with the Rv values for each rainfall depth category.
7) Total annual runoff was estimated as the product of the weighted Rv with the observed average annual rainfall depth at National Airport (108 cm)

Estimated Annual Phosphorus Loads (lb/acre):

Annual loads were estimated as a product of the estimated annual runoff depth and an assumed phosphorus concentrations (0.2 mg/L for "Closed" canopy and 0.3 m/L for "Single" tree setting). Data were converted from cm-mg/L to lb/acre.

4.2.8 CAST DATA FROM MONTGOMERY COUNTY

As a comparison, estimated annual phosphorus loads were compared to estimates derived from the Chesapeake Bay CAST Model. Downloaded data were Edge of Stream Phosphorus loads (lb/ac) for each load category in Montgomery County. A customized scenario without any BMPs implemented was used to develop these loads, using other assumptions from the 2020 Progress Run. Estimates for Turf and Canopy Over Turf were calculated as a weighted average of MS4 and Non-Regulated values from CAST, based on the areas of MS4 and Non-Regulated land in these categories in Montgomery County. The value for True Forest was estimated as one reported number from CAST for True Forest.

4.3 Statistical Comparisons and Relationships

Analyses relied on Least Squares regression to develop relationships between rainfall and runoff, rainfall and interception, and soil moisture and VPD and transpiration. For transpiration, a mixed linear model, combined with a repeated measures ANOVA and a post-hoc Tukey test was used to determine if differences between regression parameters were significant.

4.4 Ecohydrological Typology for Urban Trees

This project served as a "proof of concept" for developing an urban tree typology, testing whether trees could be characterized based on a set of common characteristics. Developing this typology includes four steps:

1. Delineate the Tree Canopy
2. Define Ecohydrological Landscape Characteristics (ELCs)
3. Extract appropriate ELCs from remote sensing and geospatial data products
4. Input data into statistical models to develop a typology.

4.4.1 DATASETS USED FOR THE ANALYSIS

This analysis relies on three publicly available datasets, available at the state or region scale (Table 5). The rationale for this decision is that if an entire region or state (such as Maryland) can make this data available, it is reasonable to expect more regions to have this type of information in the future.

Table 5. Datasets used in the typology analysis.

	Resolution	Source	Organization	Year
LiDAR	0.7 m pt spacing	md.imap.gov	Maryland	2018
Land Cover	1 m	www.chesapeakeconservancy.org	Chesapeake Conservancy	2013/2014
Aerial Imagery	6 in	md.imap.gov	Maryland	2017

4.4.2 DELINEATING THE TREE CANOPY

This study focused on the first three steps of the analysis, using data from Montgomery County. LiDAR data from Maryland (from md.imap.gov), was classified using LASTools. The primary classifications were high vegetation, medium vegetation, low vegetation, building, and ground. The classified file was used to create a three-foot resolution Digital Surface Model (DSM) and Digital Elevation Model (DEM). The first returns from high vegetation, medium vegetation, and ground were be used for the DSM. This allowed for the development of a DSM without buildings. The ground points alone were then used to create the DEM. The DEM was subtracted from the DSM to create a canopy height model. Values in building gaps were set to NoData using a building shapefile provided by Montgomery County.

4.4.3 DEFINING ELCS FOR THE TYPOLOGY MODEL

An initial set of candidate ELCs were selected from a literature review, and then refined using a decision tree (Figure 10), which selects characteristics using a series of six questions. The goal is to select characteristics that influence hydrology and can be influenced by design or management and then refining the list based on data availability.

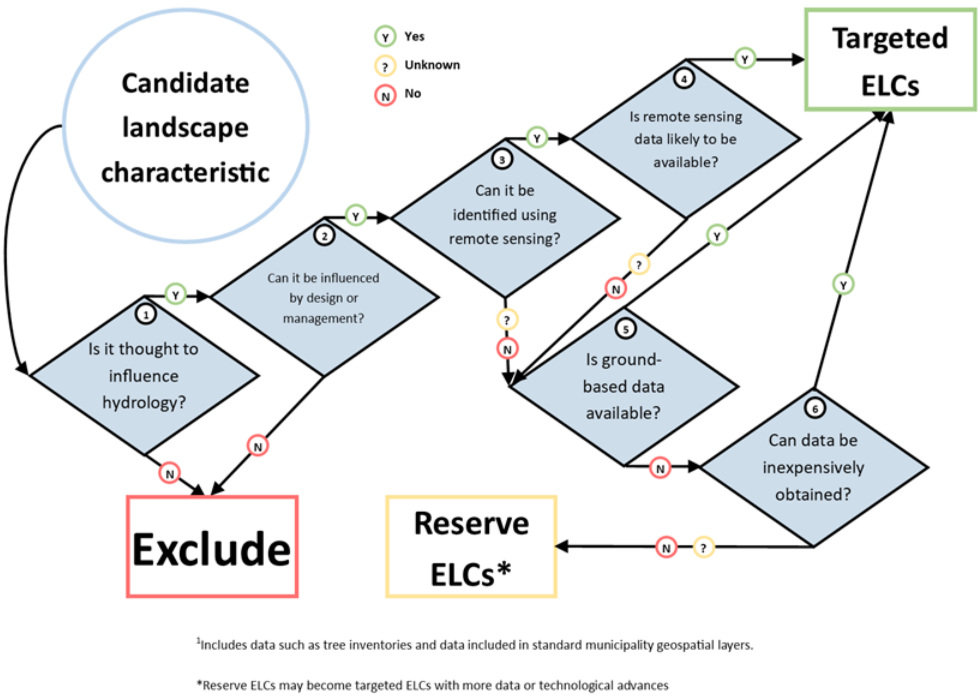


Figure 10. Decision Tree Used to Select ELCs for the Typography

4.4.4 EXTRACTING DATA AND DELINEATING BUFFER ZONES

Data were extracted using existing geospatial data. An important aspect of the tree-based approach is that each individual tree is classified based on its characteristics as well as the surrounding conditions. To achieve this goal, four concentric fixed-width circular buffers (radius of 3 m, 6 m, 9 m, and 12 m) are created around each tree location, and several metrics are collected within the buffered area. The buffers are then divided into quadrants which will provide more context about the landscape surrounding each tree (**Figure 11**).

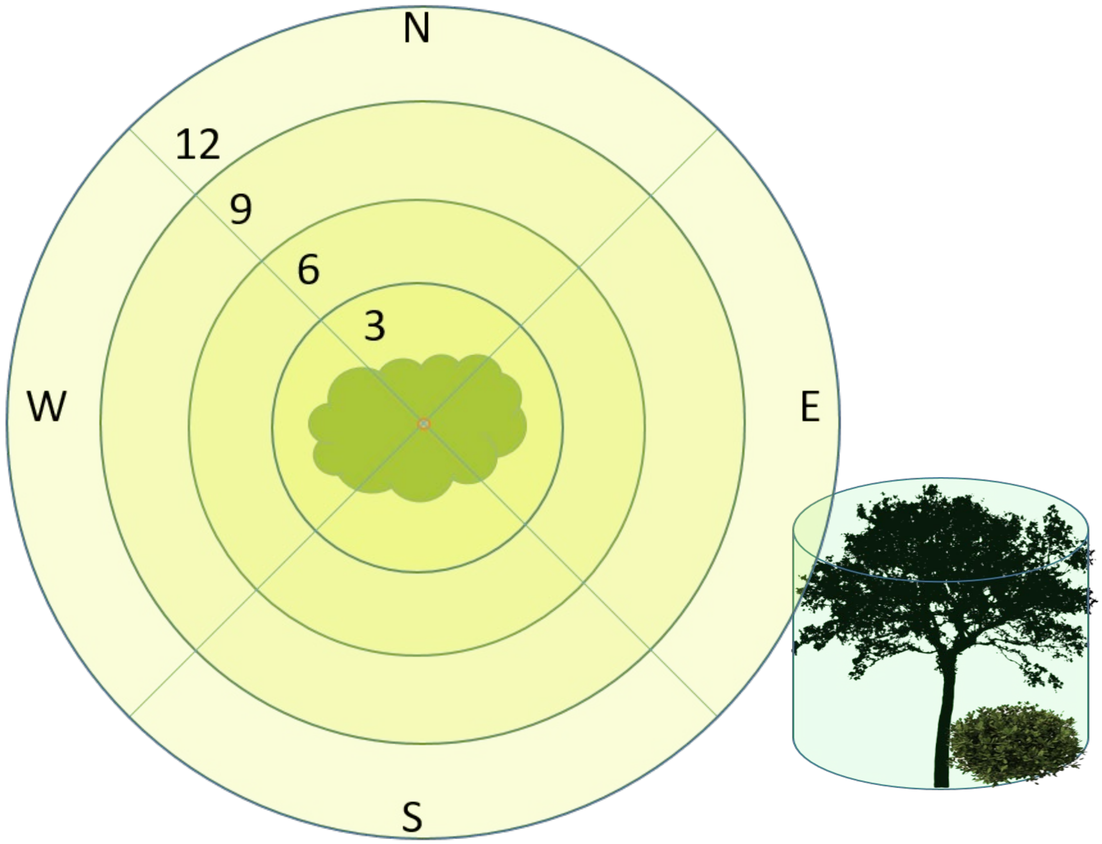


Figure 11. Concentric circles used to define individual trees characteristics and surroundings.

5 RESULTS AND DISCUSSION

Constraints of project funding, project setup and coordination limited the sample periods to two growing seasons from June to December 2018 and April through October 2019. Below are data summaries, analysis and relevant comparisons to reviewed literature as developed through this project.

5.1 Climate Data

Climate data that provided ambient temperature, vapor pressure deficit, precipitation (outside and underneath canopy) and soil moisture were consistently documented for the two growing seasons on both project sites. Soil moisture reported is based on data at 30 cm depth within the dripline of the trees with sap flow monitoring. Figures 12 and 13 display mean daily air temperature for closed canopy site (a) and single and cluster sites (b); mean daily relative humidity for closed canopy site (c) and single and cluster sites (d); mean daily vapor-pressure deficit (VPD) for closed canopy site (e) and single and cluster sites (f); daily total precipitation for closed canopy site (g) and single and cluster sites (h); mean daily soil moisture in the closed canopy (i), single and cluster sites (j). Due to the later date of soil moisture sensors installation, there was a gap in the data for the closed canopy site in June 2018. The data gaps for temperature, relative humidity, and VPD for the closed canopy site in Baltimore from May 27 to June 12, 2019 were due to battery failure.

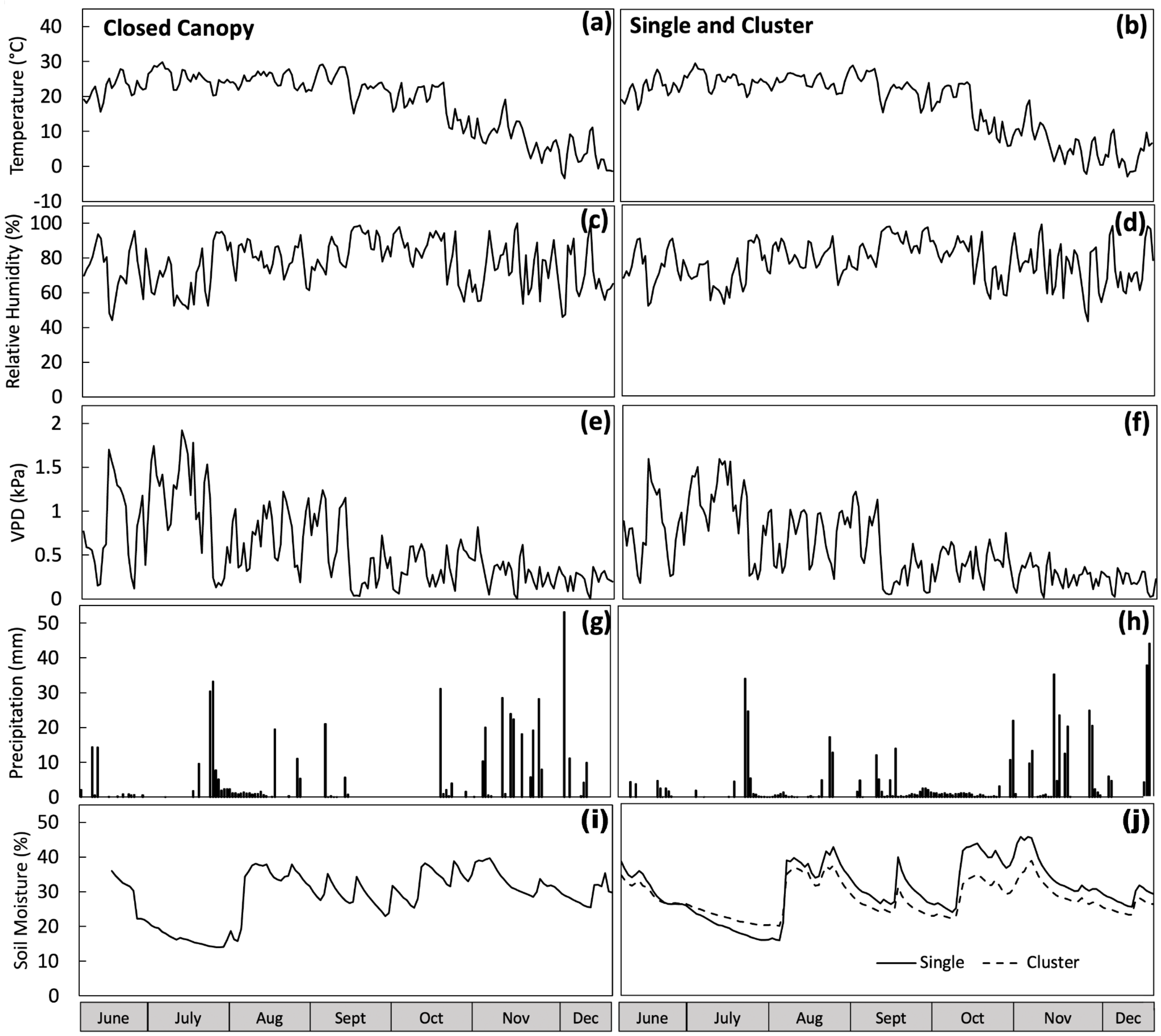


Figure 12. Microclimate data from June to December of 2018.

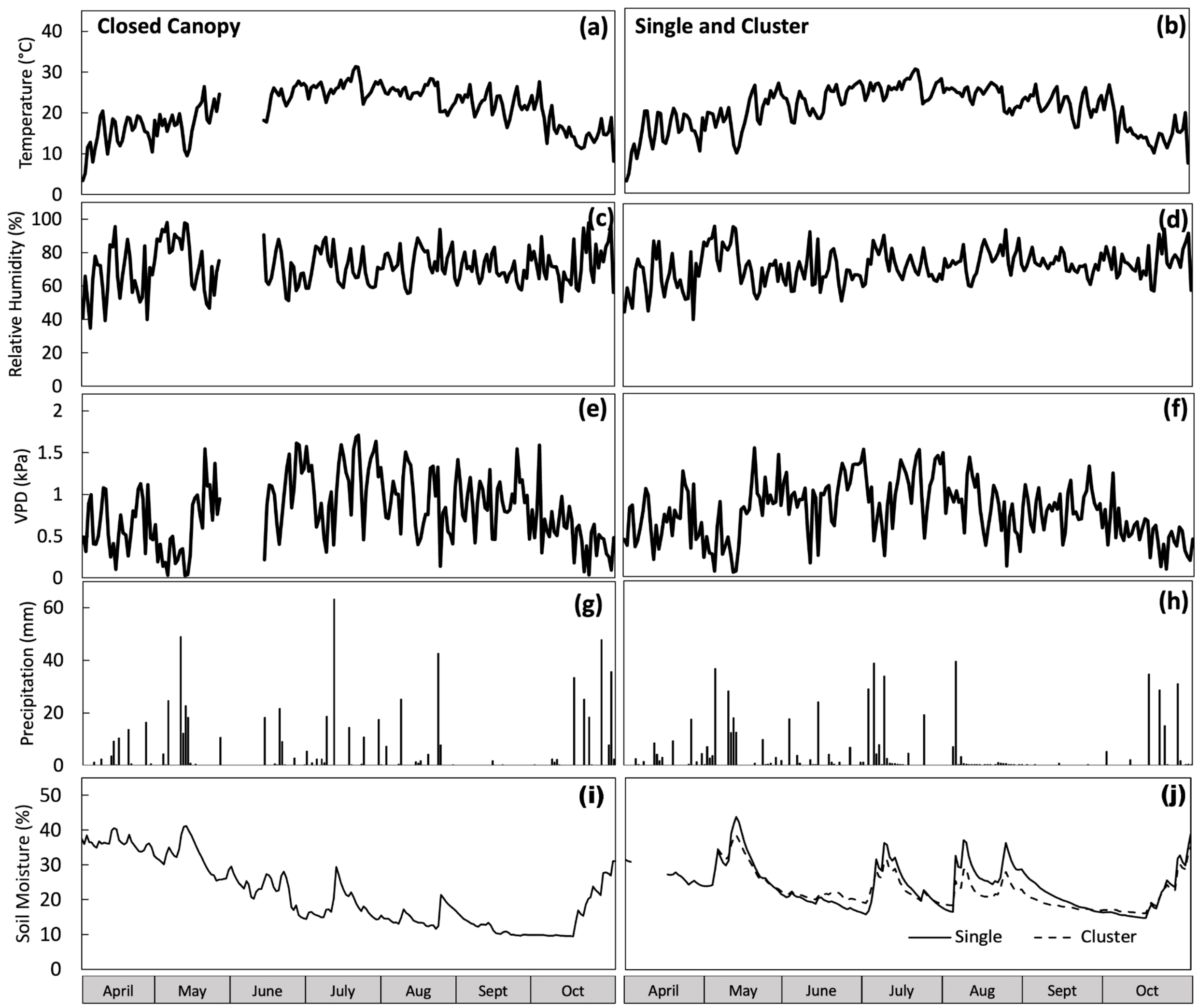


Figure 13. Microclimate data from April 1st to Nov 1st of 2019.

5.2 Sap Flow (Transpiration)

The management context reveals different daily sap flow under similar climatic conditions. Sap flow is equated with water use and therefore we report grams of water per square centimeter per day for the trees with sap flow monitors. Both the continuous values (Figures 14-15) and monthly data (Figure 16) indicate that Single trees showed the greatest sap flow consistently across the study sites.

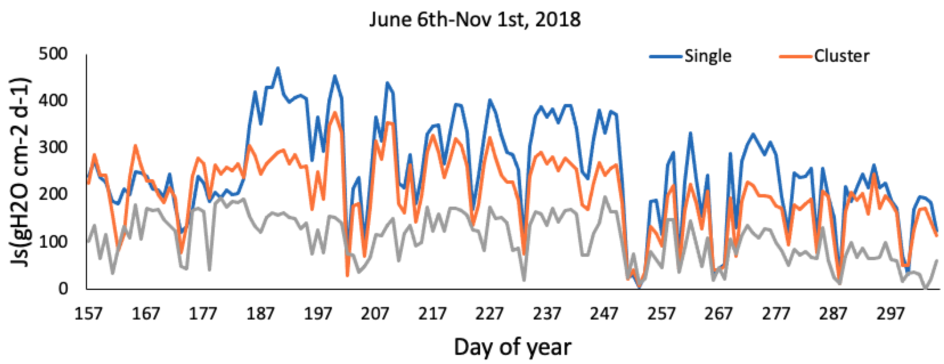


Figure 14. Time-series of the mean daily sum of sap flux in the outer 2cm (JS) measured in 2018 for all tree species in the three management contexts.

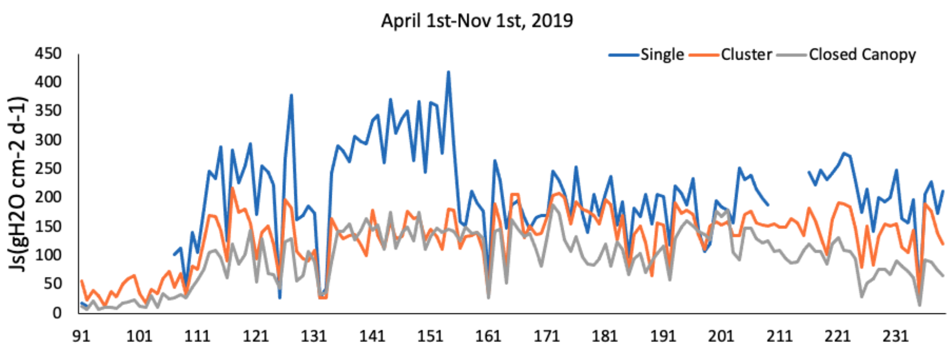


Figure 15. Time-series of the mean daily sum of sap flux in the outer 2cm (JS) measured in 2019 for all tree species in the three management contexts.

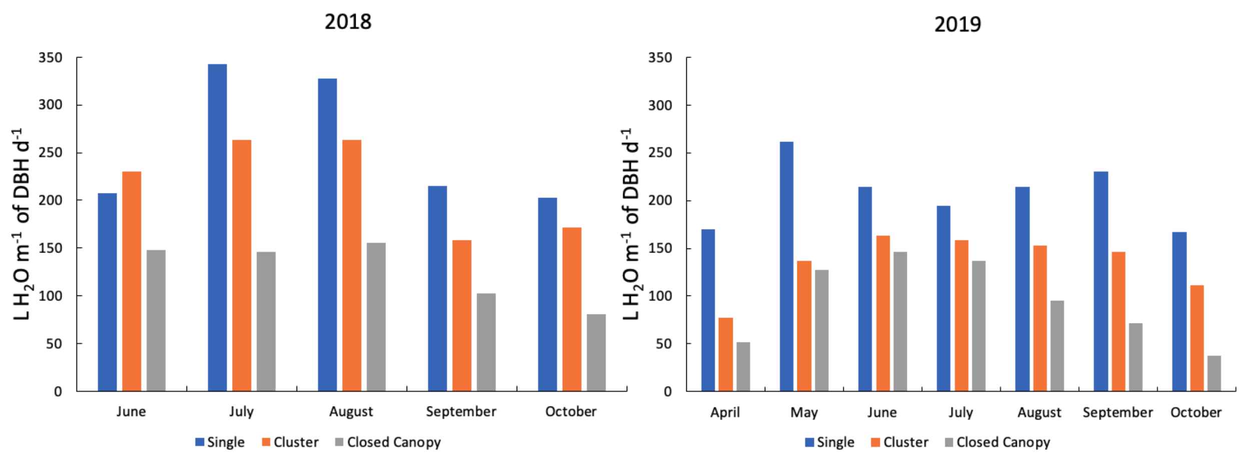


Figure 16. Monthly mean water use per meter of DBH (L/m/day) for the years 2018 (left) and 2019 (right) for all tree species in the three management contexts.

5.2.1 SAP FLOW AS A FUNCTION OF VAPOR PRESSURE DEFICIT AND SOIL MOISTURE

Vapor pressure deficit (VPD) is the difference between the amount of moisture in the air and how much moisture the air could potentially hold when it is saturated. A high VPD (greater than 1.0 kPa) means that the air can still hold a large amount of water. A low VPD indicates the air is near saturation. VPD plotted against sap flow indicated that single maples transpired the greatest with high VPD whereas individual trees in closed canopy transpired the least with high VPD.

We observed that management context significantly impacted sap flux rates and that single trees over turfgrass had the highest transpiration rates, while trees at the closed canopy site had the lowest transpiration rates as estimated by sap flux monitoring results. Figures 17 and 18 are scatter plots of mean daily sum of sap flux against vapor pressure deficit and against soil moisture to show their relationship with sap flux tendency for each management context. Trees at the single and cluster sites had greater variability in sap flux rates than at the closed canopy site. Additionally, there were seasonal differences between VPD and sap flux across the management contexts.

From our regression analyses, the single and cluster sites had a steeper slope than the closed canopy site across all time periods. This suggests that individual trees and clusters of trees over turfgrass are more responsive to VPD than trees in forest patches. Additionally, the larger intercept for the single and cluster sites when compared to the closed canopy site across all time periods can be explained by a reduced humidity at the leaf surface. Increasing stand density promotes a decrease on the rate of transpiration of individual leaves due to shielding from the microclimate (e.g., radiation and wind) (Larcher, 2003), so the fact that single and cluster sites are less buffered from environmental drivers might explain why the increase of R^2 from early summer to late summer was not observed for the closed canopy site as shown in Table 6.

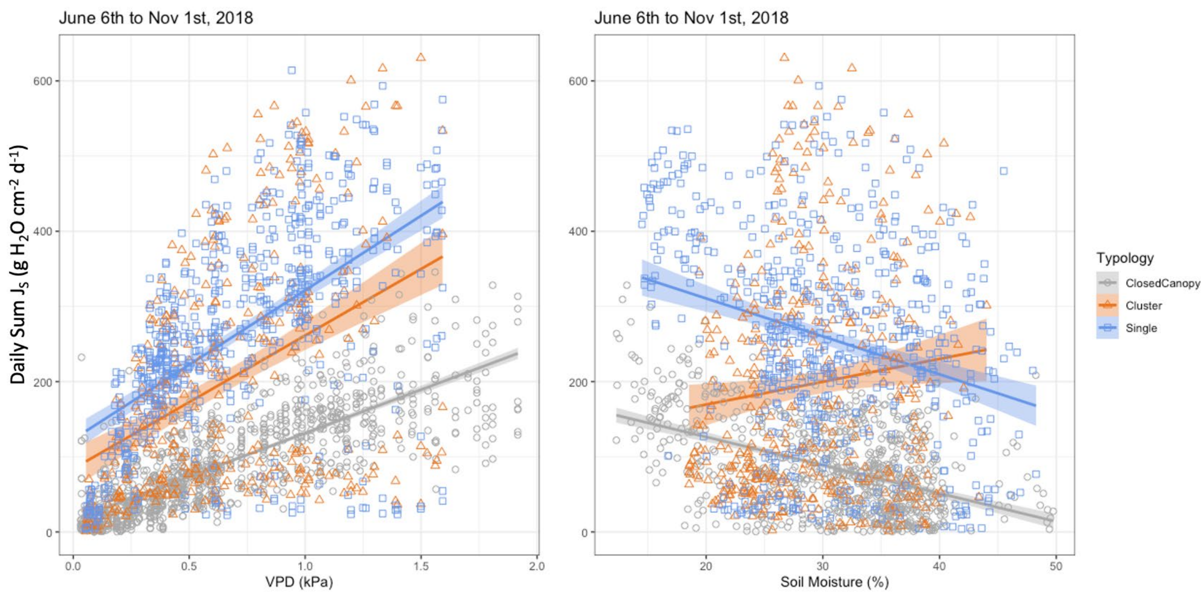


Figure 17. Mean daily sum of sap flux (JS) as a function of mean daily vapor-pressure deficit (VPD) (left) and mean daily percent soil moisture (right) for Red Maples. Each point represents a red maple tree from June 6th- Nov 1st, 2018.

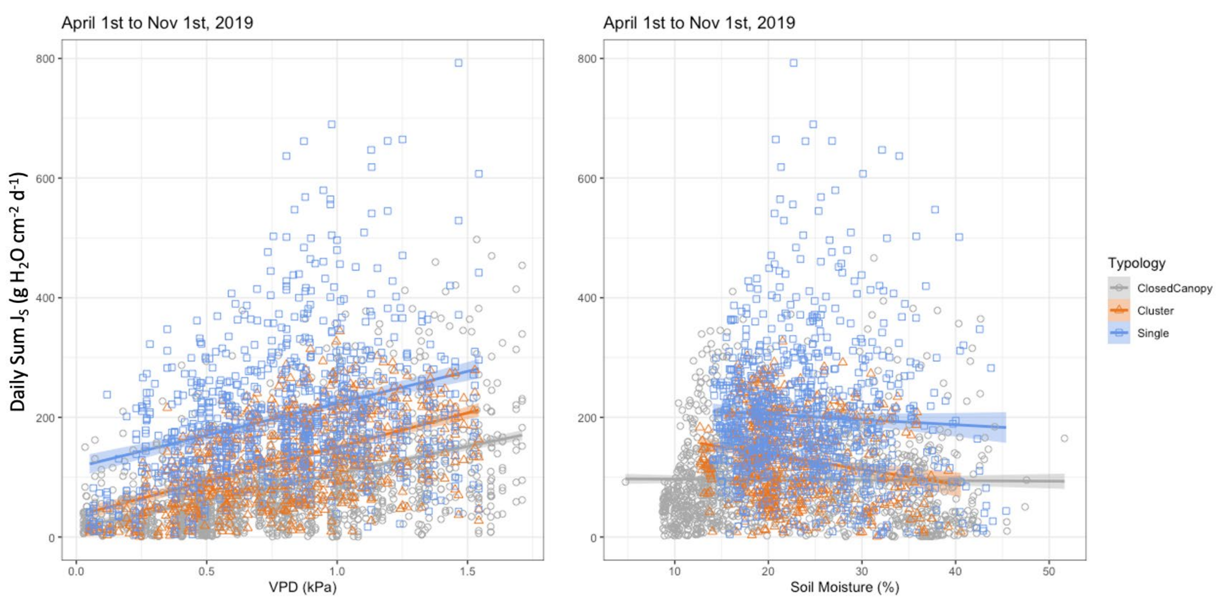


Figure 18. Mean daily sum of sap flux (JS) as a function of mean daily vapor-pressure deficit (VPD) (left) and mean daily percent soil moisture (right) for Red Maples. Each point represents a red maple tree from April 1st- Nov 1st, 2019.

For the 2018 monitoring year , Sap flux data were split into three 7-week time periods to investigate the seasonal variation of sap flux in response to VPD in Table 7. Linear regression was used to determine the association between the independent variable (VPD) and dependent variable (sap flux). Repeated measures ANOVA of the JS-VPD regression parameters showed that the slope and intercept were significantly different between single and closed canopy sites across all time periods. The slope and intercept for the single and cluster sites were more than twice the values at the closed canopy site during the late summer and fall. Based on the R^2, VPD explains more of the variability of the rate of sap flux later in the summer when compared to early summer for the single and cluster sites, but this was not observed for the closed canopy site. When comparing the regression parameters for each management context across the time periods, the slope for the closed canopy site was significantly different between early summer and late summer (p=0.001), and between early summer and fall (p=0.001). For the intercept, there was a significant difference between early summer and fall (p=0.009) for the closed canopy site.

The difference may be explained by the following analysis. During the early summer, VPD showed the most variation, while the fall period had less variation. This pattern is consistent with the change in relative humidity and temperature variation over time. During the late summer and fall, single trees had a higher rate of sap flux for the same VPD when compared to cluster and closed canopy trees.

Table 6. Red Maple trees from June 5- Nov 1, 2018. Average parameters and R^2 of sum of daily sap flux vs. daily average vapor pressure deficit (VPD) relationships of the form y=a*ln(VPD)+b. SE are shown in parentheses. Unique letters indicate cross site differences within each time period based on post hoc analysis.

			Single			Cluster			Closed Canopy	
Time Period	Dates	a	b	R^2	a	b	R^2	a	b	R^2
Early Summer	June 5-July 24, 2018	121.89	297.48	0.28	94.59	270.72	0.21	66.39	147.27	0.66
		(13.51)a	(38.21)a	(0.10)	(52.41)ab	(113.63)ab	(0.12)	(7.70)b	(15.55)b	(0.03)
Late Summer	July 25-Sept 12, 2018	139.69	370.08	0.88	104.89	281.87	0.76	40.54	122.10	0.52
		(12.51)a	(35.85)a	(0.03)	(46.26)ab	(115.10)ab	(0.16)	(3.40)b	(12.22)b	(0.04)
Fall	Sept 13-Nov 1, 2018	117.38	326.49	0.72	96.86	252.39	0.61	35.25	93.79	0.58
		(11.50)a	(27.26)a	(0.03)	(37.80)ab	(92.61)ab	(0.12)	(4.58)b	(12.07)b	(0.05)

While it was somewhat surprising that soil moisture was not correlated with transpiration, there are a few possible explanations for this finding. First, the soil moisture was measured only in the first 30 cm of soil. It is possible that trees draw from greater soil depths when the soil is dry. Second, but not quite as obvious, is that high soil moisture may have a "push-pull" effect. Both the i-Tree Hydro model and the Water Balance Model (Hynicka and Caraco, 2018) model the soil profile as storage that is filled by infiltration, and subsequently drained though transpiration and deep soil infiltration. Consequently, while soil storage is necessary to support transpiration, high soil moisture may also correlate with climate conditions such as clouds and high humidity that are not conducive to higher amounts of transpiration (i.e., a lower VPD). As a future project, data can be analyzed as a time series, perhaps including both VPD and soil moisture as variables, and incorporating soil moisture in preceding days as well as the same day.

5.2.2 SAP FLOW INFLUENCE OF TREE SPECIES AND SETTING

Converting mean daily sap flow to a water use per DBH metric (Figure 8) indicated that the difference between species was not as dramatic as the difference between settings. One interesting result was that, while the median water use in the Closed Canopy setting was higher than Red Maple for the 2018 year, it was lower in 2019. Since monitoring in 2018 started in June, while 2019 monitoring started in April, this finding supports the initial hypothesis that Tulip Poplars have higher peak Transpiration, but red maples achieve greater transpiration over the entire growing season. Since Red Maple was the only tree present in all three settings, the comparisons between all three settings across both years were compared (Figure 19). The results, indicate that transpiration is statistically higher in the Single Tree setting than in the Closed Canopy setting, while the Cluster group is not significantly different than either group (Figure 20).

These results do not support the initial hypothesis that the more complex tree canopy would achieve greater transpiration, but this result is partially explained by the fact that sap flux was measured on a "per-tree" basis. In the clustered and closed canopy settings, the per-area transpiration is higher, due to the greater tree density (trees or DBH per acre). In addition, it is not surprising that a single tree could achieve greater transpiration due to greater exposure to wind and sun, and potential greater leaf area in the single tree setting due to lack of shading from other trees. From a stormwater perspective, the per-area value may be more useful as a planning tool. At the watershed scale, it is important to target areas that can achieve stormwater benefits, and while planting a single tree in the open may achieve more transpiration than planting the same tree within a forest setting, planners may want to compare the value of preserving types of forest patches (on a per-acre basis).

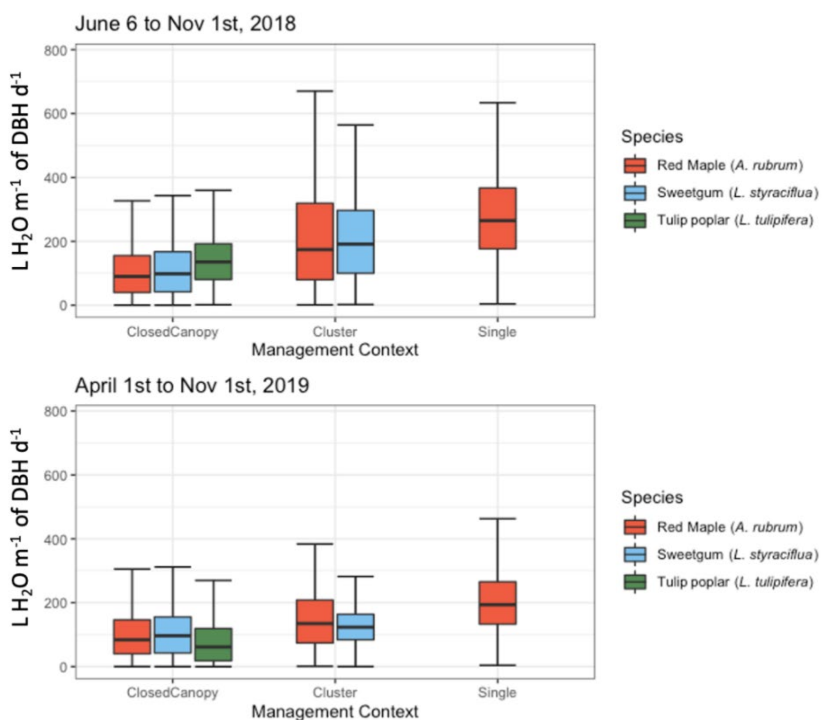


Figure 19. Unit Water Use (L/m-DBH/day) for the years 2018 and 2019.

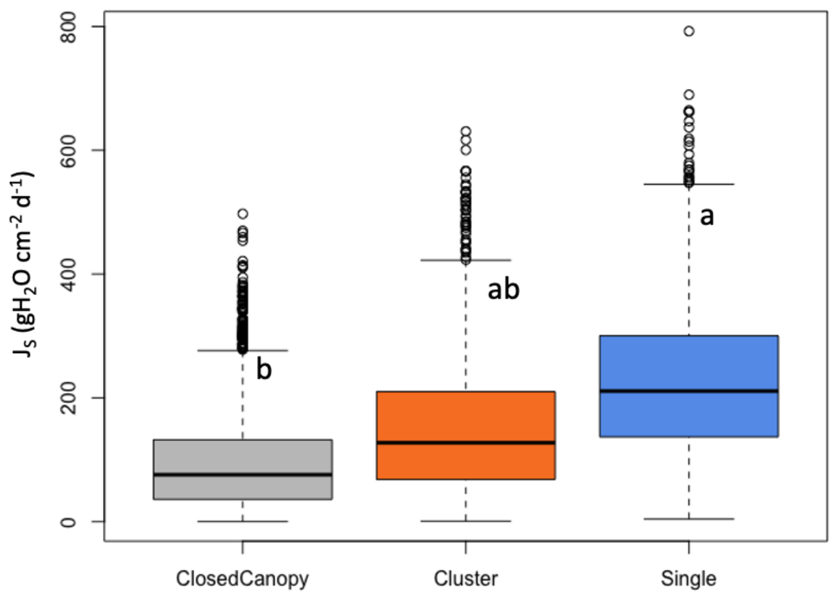


Figure 20. Average Daily Sap Flux for Red Maples in Three Settings ("Single" sap flux is higher than Closed Canopy, and cluster is not significantly different than the other settings).

5.3 Interception

Although the results were highly variable, they suggest that the tree canopy does provide interception, and that the amount of interception varies depending on the tree canopy setting and the storm depth. Consequently, interception values are represented as a fraction of rainfall rather than a storm depth or volume. The median interception fraction was generally higher during the growing season (April through October), except for in the Cluster setting, where the median capture appeared to be slightly higher in the non-growing season, except for in the Cluster setting. Further, an initial review of the data suggested that the fraction of rainfall interception is quite similar between the different settings (Figure 21; Table 7).

It is somewhat counterintuitive that any interception was observed during the non-growing season. Although it was not specifically measured, some precipitation captured by branches and directed to the ground as stemflow would not have been captured using the methodology of this study, since interception was simply quantified as the difference between rainfall outside the canopy, and rainfall measured below the canopy.

The method was also somewhat sensitive to storm selection. One potential measurement error included storm burst type storms that were observed only at the location under or outside of the canopy. Another potential error source was that rainfall does not always fall uniformly through the tree canopy, resulting in concentration of observed throughfall at a few points under the canopy. Consequently, the rain gage under the canopy may underestimate interception in cases where the concentrated rainfall was not captured by the gage or overestimate it when the rainfall is not captured by the gage. For this analysis, we did allow "negative interception" values to be included, but we excluded storms where the throughfall depth was more than 50% greater than the rainfall depth. At the other end of the spectrum, we excluded events where no throughfall was observed.

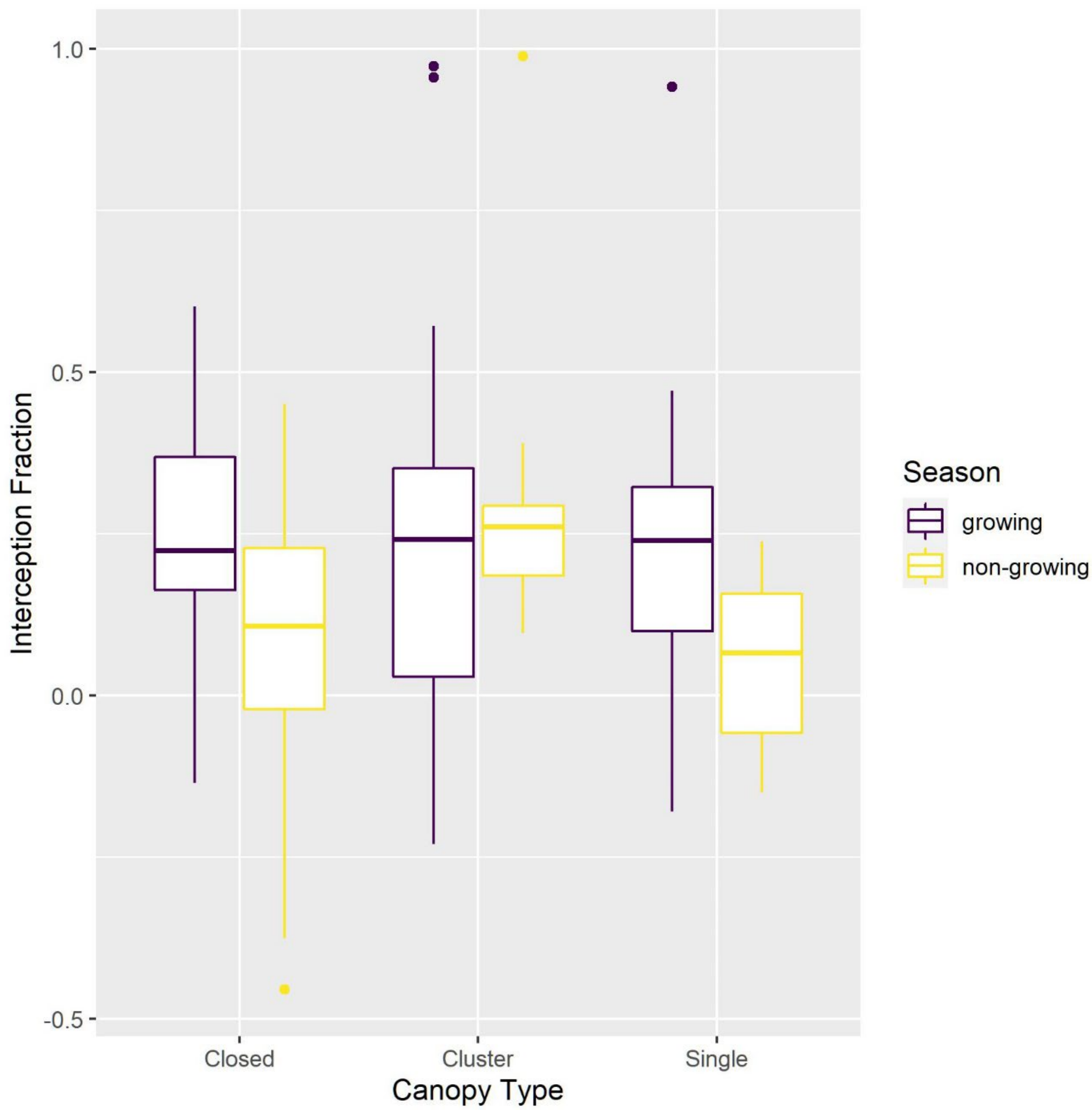


Figure 21. Interception during the Growing and Non-Growing Season for each Canopy Type

Table 7. Median Interception fractions in each setting

Season	Canopy	N	Median
growing	Closed	38	0.224
growing	Cluster	34	0.242
growing	Single	18	0.240
non-growing	Closed	42	0.107
non-growing	Cluster	10	0.261
non-growing	Single	17	0.066

Since the tree typology (or canopy type) was confounded with the geographic location, each canopy type did not experience the same rainfall events. In addition to filtering rainfall to eliminate outliers experienced only in certain settings (i.e., rainfall events above 6 cm), linear regression models were developed to compare both the interception depth and the interception fraction to rainfall depth for the growing season only (Figure 22 and Table 8). While the rainfall depth had a significant relationship to interception depth, the regression explained a small amount of the overall variability, and rainfall was not significantly related to the interception fraction (Figure 21; see Appendix A for statistical model results). Since there was no significant correlation between rainfall and interception fraction, and no significant difference between any of the canopy types, we characterized seasonal interception for all canopy types as a single group. Across all storm events the total interception capture was 22% of rainfall during the growing season, and 9.6% of rainfall during the non-growing season.

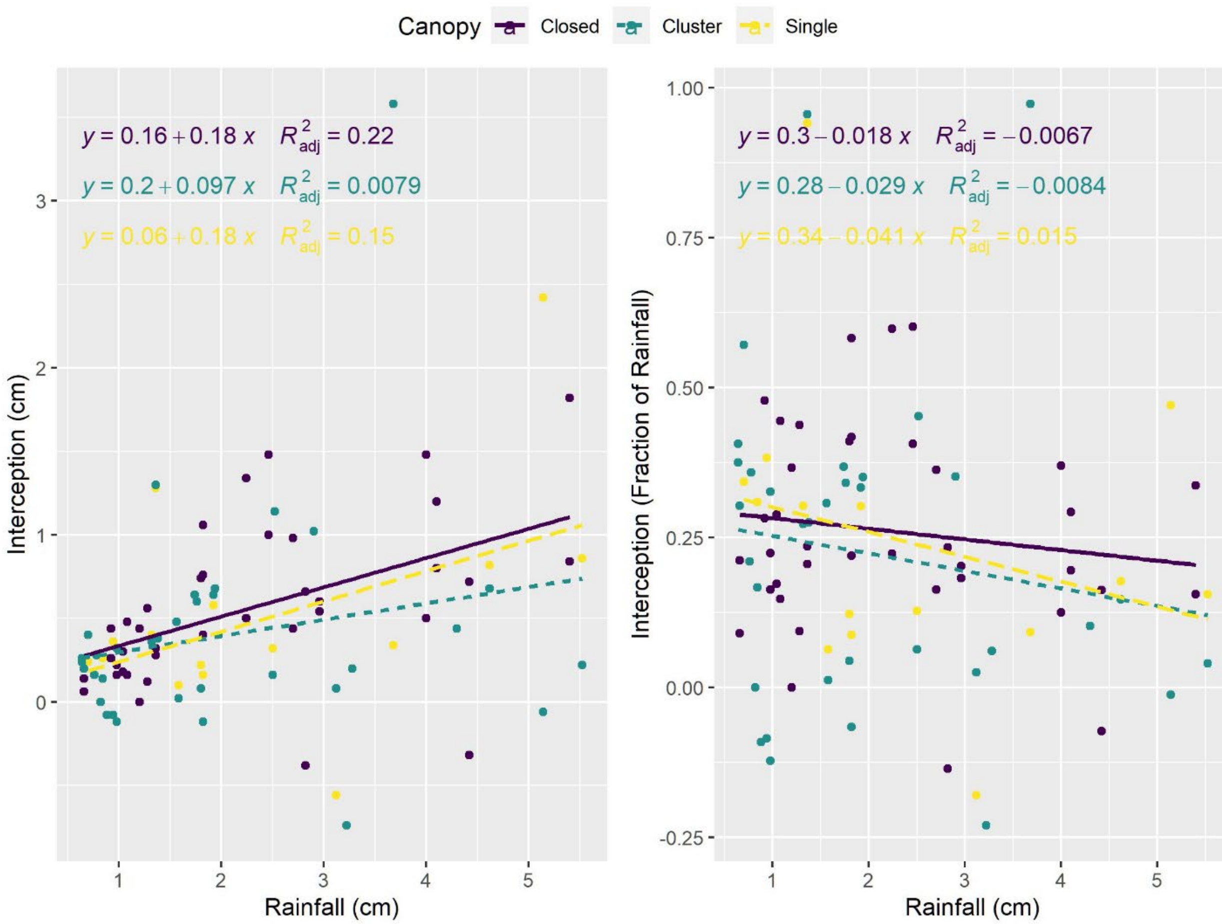


Figure 22. Interception and Interception Fraction as a Function of Rainfall

5.4 Surface Runoff and Infiltration

Estimates of surface runoff and infiltration relied on fewer rainfall events, since estimating runoff required both soil moisture and precipitation data. Further, very short storms were not considered because it was not possible to estimate runoff depth using the model chosen. As a result, runoff was calculated for between eight and twelve storms in each setting over the monitoring period. The runoff calculation spreadsheets used to arrive at the runoff depths summarized here are included as an attachment to this document. In this study, we were most interested in the Runoff Coefficient (Rv), which represents the fraction of rainfall converted to runoff. The Throughfall runoff coefficient (Rv-T) reflected the effects of trees on soil characteristics and soil moisture (through ET), while the rainfall runoff coefficient (Rv-R) represents both those impacts on the soil profile and Interception in the tree canopy. An initial view of the data suggests that both runoff coefficients are higher for the Cluster and Single canopy types than for the Closed Canopy type (Figure 23 and Table 8).

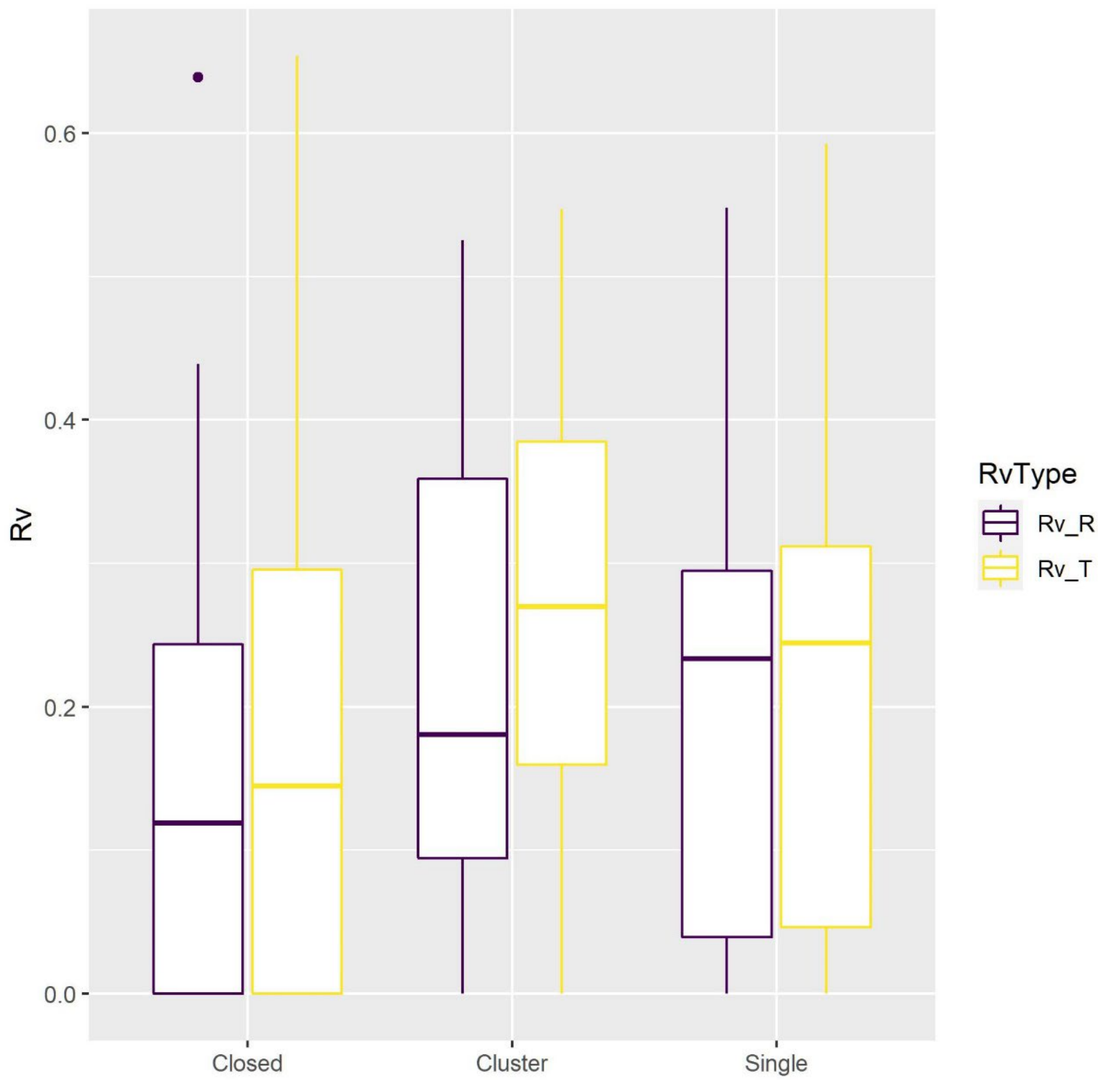


Figure 23. Runoff Coefficients for Each Setting

Table 8. Median Runoff Coefficients compared to Rainfall (Rv_R) and Throughfall (Rv_T)

Canopy	n()	median(Rv_R)	median(Rv_T)
Closed	12	0.119	0.145
Cluster	8	0.180	0.270
Single	11	0.234	0.244

Both runoff coefficients were highly variable and correlated with the depth of runoff or throughfall. The results for the Throughfall coefficient (Figure 24), indicate that the runoff coefficient increases with throughfall depth for all three settings. Although the slopes appear to be different between settings, these differences are not significant (See Appendix A for statistical model results). Although each model accounted for a small amount of the variability in the Rv coefficient the overall relationship between Throughfall depth and Rv_T was significant.

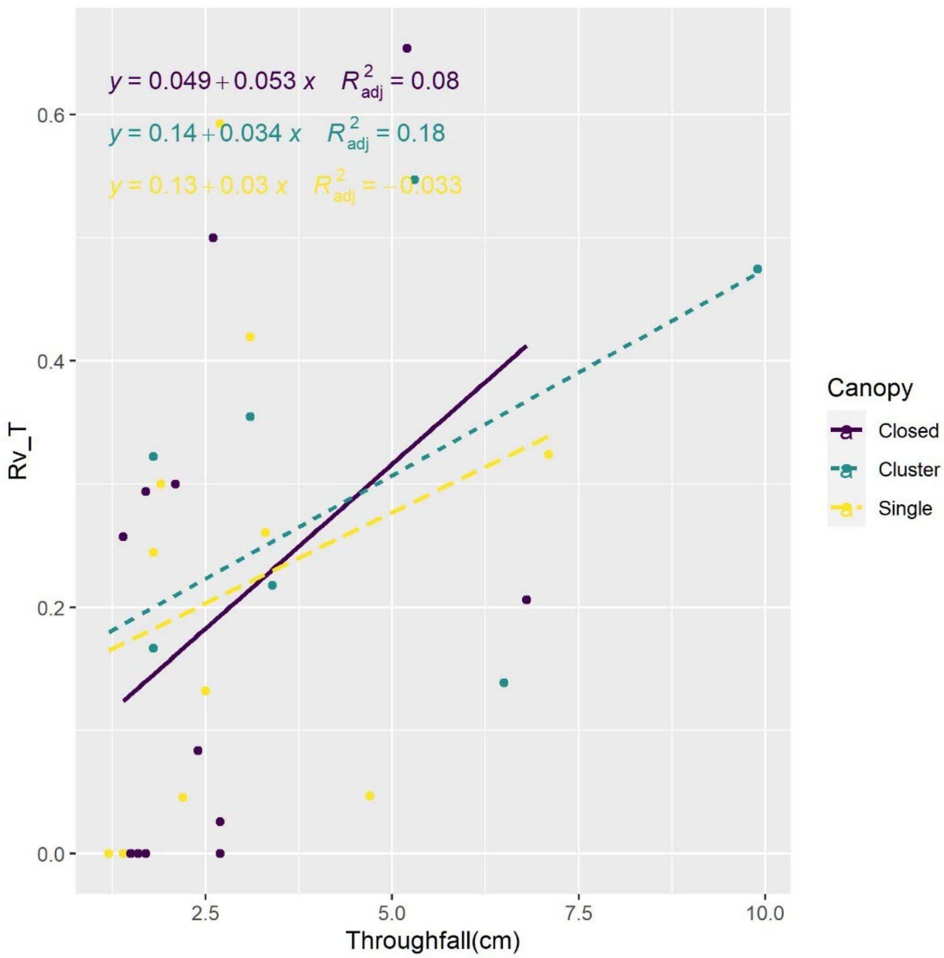


Figure 24. Runoff Coefficient (Rv_T) vs Throughfall Depth (cm)

For the Closed Canopy and Single settings, it was possible to develop a weighted annual estimate of the Throughfall fraction and runoff coefficient (as a fraction of throughfall). Unfortunately, only storm could be modeled in the "low" category for the Cluster setting, so we did not estimate annual coefficients for this setting. The weighted average estimated total coefficients for rainfall depths in "High" (>5 cm), "Medium" (2.5=5 cm) and "Low" (1.25-2.5 cm) depths. It is assumed that rainfall depths <1 cm do not produce runoff. Using data from Reagan National Airport between January 1, 2000, and December 31, 2019, we weighted these coefficients based on the fraction of rainfall falling within each of these categories. The results of this analysis are summarized in Table 9.

Table 9. Precipitation/ Throughfall and Interception Over the Study Period

Canopy	Precipitation Category	Weight	Total Precipitation (cm)	Total Runoff (cm)	Rv_R
Closed	Low (>1-2.5 cm)	0.37	12.88	1.49	0.12
	Medium (>2.5-5 cm)	0.26	11.58	1.57	0.14
	High (>5 cm)	0.14	13.56	4.80	0.35
				Weighted Coefficient	Rv_R = 0.13
Single	Low (>1-2.5 cm)	0.37	7.30	1.01	0.14
	Medium (>2.5-5 cm)	0.26	15.30	13.8	0.27
	High (>5 cm)	0.14	12.70	11.8	0.20
				Weighted Coefficients	Rv_R = 0.15

5.4.1 COMPARISON TO CHESAPEAKE BAY PROGRAM CREDITS

A simple comparison of the observed annual runoff coefficients to the CBP credits was developed using an assumed phosphorus concentrations and multiplying the annual runoff coefficient times an assumed annual rainfall depth of 42.5". Using these assumptions and comparing the estimated values to Turf and Turf Over Canopy loads from Montgomery County, both the Single and Closed canopy types have loads lower Canopy Over Turf, but not as low as loads from Forest. Phosphorus concentrations were not measured in this study, and have huge impact on the estimated loads, however.

Table 10. Comparison of Phosphorus Loading to CBP Load Estimates

Canopy	Estimated Annual Runoff (inches)	P Load (lb/acre/year)	Source
Closed	5.43	0.25	Calculated assuming a concentration of 0.2 mg/L in Closed Canopy and 0.3 mg/L in Single
Single	6.41	0.44	
Turf	N/A	0.85	CAST Model Results for Montgomery County
Canopy Over Turf	N/A	0.64	
Forest	N/A	0.022	

5.4.2 CURVE NUMBER COMPARISONS

The Water Balance Model (Hynicka and Caraco, 2017) relies on a revised curve number method, which is then adjusted to account for the presence of trees, and for soil moisture. This method relies on a "base" curve number to reflect turf, but then subtracts 4 from this value to reflect the effects of trees on soil. The adjusted curve number is 70 in average moisture conditions, but ranges from 50 to 84 depending on antecedent moisture conditions. As a quick comparison, we "back calculated" the curve number based on calculated throughfall and runoff for each observed event (Figure 25). This analysis was restricted to events with at least 2.5 cm of throughfall depth, since the Curve Number method is not designed to work well for very small storms. For events that produced no runoff, a default Curve Number of 50 was assigned. The results are toward the higher end of that spectrum, with some events having curve numbers as high as 95. Curve numbers were higher as the Initial Moisture Content increased, but conditions were generally quite wet during the study period. Typically, the Curve Numbers for the highest antecedent moisture conditions are associated with soils at Field Capacity. In this study, field capacity was exceeded for many of the storm events, approaching saturated soil conditions at the beginning of the storm event. Although there are insufficient data to confirm or refute the assumptions of that model, these results are consistent, and we do see a general but weak correlation between moisture content and curve number. It is not possible to determine from this analysis whether the Canopy Type had a significant impact on the runoff curve number, given the numerous sources of variability and number of data points.

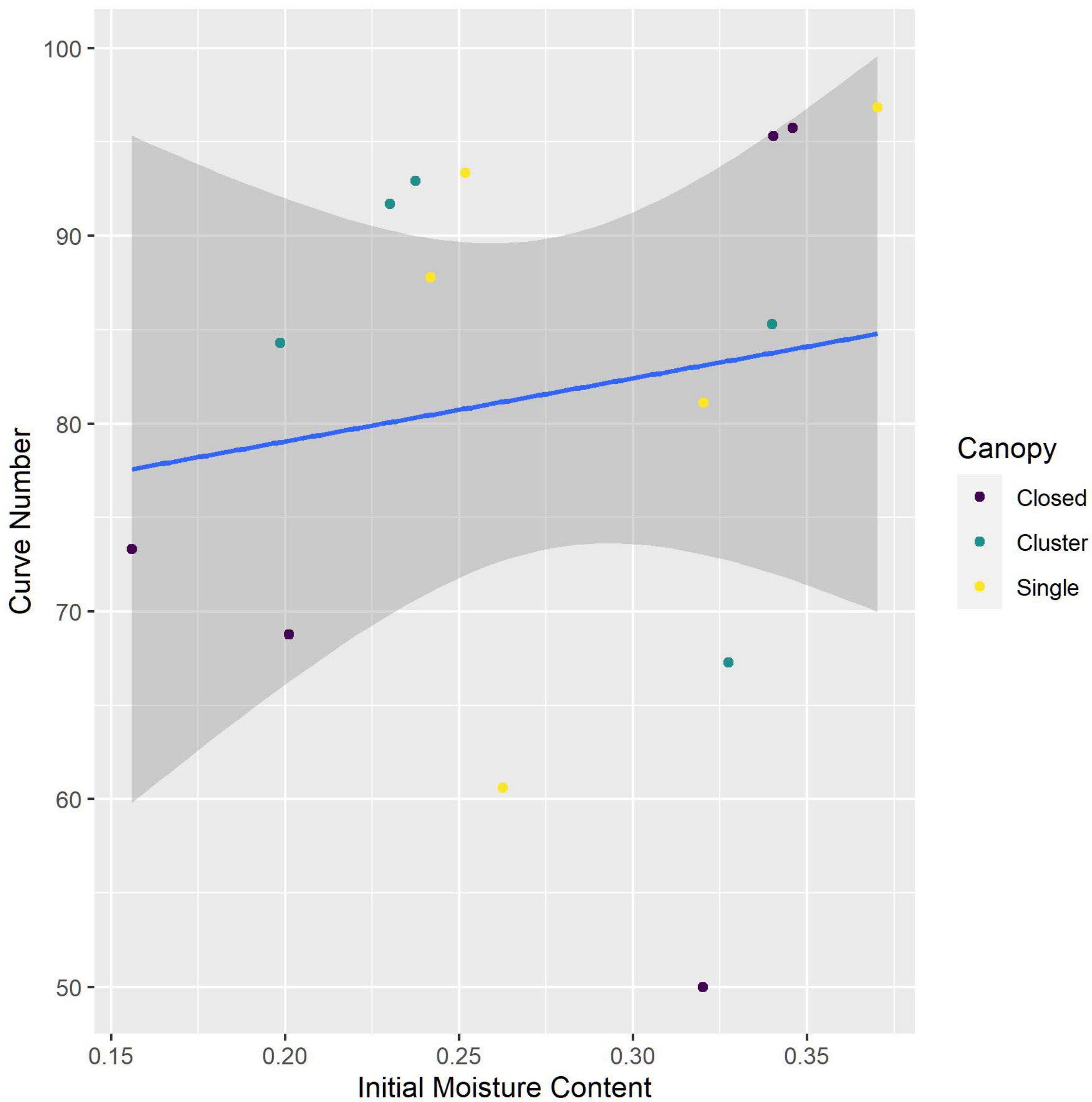


Figure 25. Curve Number Vs Soil Moisture Content for Events > 2.5 cm

5.5 Ecohydrological Typology

Data from Montgomery County were used to test the potential for using the typology in an urban setting. The results suggest that, based on the available data, this process is feasible, and work is ongoing through the University of British Columbia to continue the statistical analysis and model development process. As a part of this project, the study team developed a list of ELCs, extracted data from available layers and tested identifying and characterizing individual trees in portions of the County.

5.5.1 ELC SELECTION

Beginning with a long list of candidate parameters, the study team selected a list of ELCs suitable to develop the typology (Table 11). The final list of thirteen Target ELCs could be derived from

Remotely Sensed (RS) data, with the exception of Tree Species, which was available through i-Tree ECO.

5.5.2 DATA EXTRACTION

As a part of this study, a Tree Height Model was developed for the entire urbanized portion of Montgomery County (Figures 26 and 27), and several other parameters were extracted using RS data (Table 11).

5.5.3 IDENTIFYING AND CHARACTERIZING INDIVIDUAL TREES

To be successful, the typology relies on an automated process to identify individual trees. This process was tested in an area within Montgomery County, by comparing the results of automated tree delineation, with hand-delineation. The results (Figure 28) suggest that individual trees can be delineated by hand using LiDAR data and the R Studio package LidR. The results suggest that it automated tree-delineation adequately matches hand-delineating individual trees in the urban environment. Finally, buffers were drawn around identified trees (Figure 29). These buffers have been intersected with extracted data in test areas successfully, and some analysis has been run on them. In developing the typology, metrics such as the number of pixels in each land cover category, number of directions where each category occurs, tree density, and distance to the next nearest tree or group of trees will be used to characterize each individual tree.

Table 11. Candidate ELCs Selected Using the ELC Decision Tree

Candidate Characteristic	Linked to design/mgmt	Identifiable via RS	RS data available	GB data available	GB data obtainable	Decision
Tree species	Yes	Yes[b]	No[1]	Yes[6]	N/A	Target
Evergreen/Deciduous	Yes	Yes[c]	Yes[1,2,3]	N/A	N/A	Target
Phenology	Yes	Yes[d,e]	Yes[4]	N/A	N/A	Target
Tree size	Yes	Yes[f]	Yes[2]	N/A	N/A	Target
Tree health	Yes	Yes[g,h]	Yes[1,3]	N/A	N/A	Target
Leaf area index	Yes	Yes[i]	Yes[1,2,3]	N/A	N/A	Target
Leaf morphology	Yes	No	N/A	No	No	Reserve
Branch angle	Yes	No	N/A	No	No	Reserve
Bark texture	Yes	No	N/A	No	No	Reserve
Evapotranspiration rate	Yes	Maybe	Maybe[1,3,5]	No	No	Reserve
Root structure/depth	Yes	No	N/A	No	No	Reserve
Rooting volume	Yes	No	N/A	No	No	Reserve
Water holding capacity	Yes	No	N/A	No	No	Reserve
Fertility	Yes	No	N/A	No	No	Reserve
Compaction	Yes	No	N/A	No	No	Reserve
Drainage	Yes	No	N/A	No	No	Reserve
Green infrastructure	Yes	No	N/A	No	No	Reserve
Least limiting water	Yes	No	N/A	No	No	Reserve
Surrounding land cover	Yes	Yes[j]	Yes[1,2,3]	N/A	N/A	Target
Impervious surfaces	Yes	Yes[k]	Yes[1,2,3]	N/A	N/A	Target
Watershed position	No	N/A	N/A	N/A	N/A	Exclude
Pollution	No	N/A	N/A	N/A	N/A	Exclude
Tree density	Yes	Yes[l]	Yes[1,2,3]	N/A	N/A	Target
Crown spacing	Yes	Yes[l]	Yes[1,2,3]	N/A	N/A	Target
Shrub cover	Yes	Yes	Yes[1,2,3]	N/A	N/A	Target
Grass cover	Yes	Yes	Yes[1,2,3]	N/A	N/A	Target
Other ground cover	Yes	Yes	Yes[1,2,3]	N/A	N/A	Target
Slope/aspect	No	N/A	N/A	N/A	N/A	Exclude
Structural complexity	Yes	Yes	Yes	N/A	N/A	Target

[1]hyperspectral, [2]lidar, [3]multispectral, [4]multi-temporal multispectral, [5]eddy flux data, [6]i-Tree Eco & Urban FIA

GB = ground-based, RS = remote sensing. Many of the characteristics are from the list compiled by Berland, et al.

Table 12. Data Layers Extracted from Geospatial Data

ELC	Extracted	Extracted from
Tree size	Height, crown width	LiDAR
Surrounding land/ground covers	Percent and directions of different types of land/ground covers	CC land cover dataset and buffers
Impervious surfaces	Percent and directions of impervious surface within buffer zones	CC land cover dataset and buffers
Tree density	Number of trees (or area of canopy) within buffer zones divided by size of buffer zone	LiDAR and Buffers
Crown spacing	Distance to nearest tree	LiDAR
Structural Complexity	Number of repeats	LiDAR

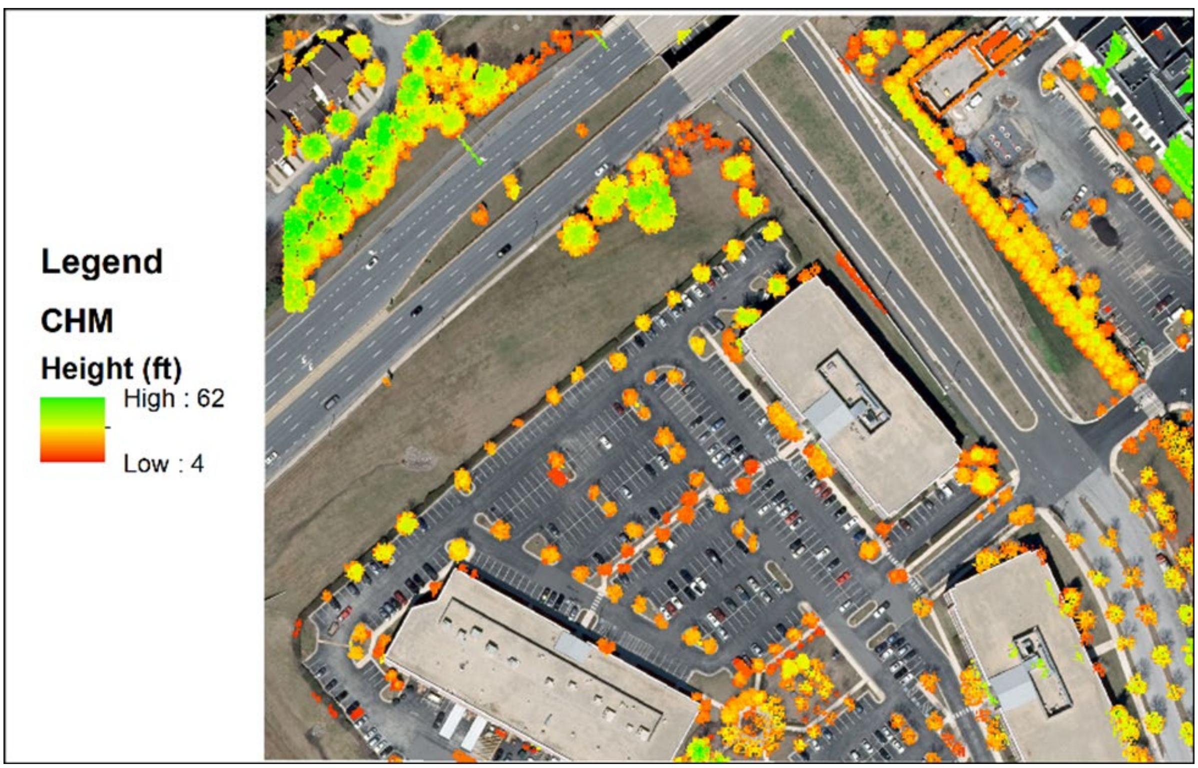


Figure 26. Canopy height model of a subset of the study area, developed from LiDAR data.

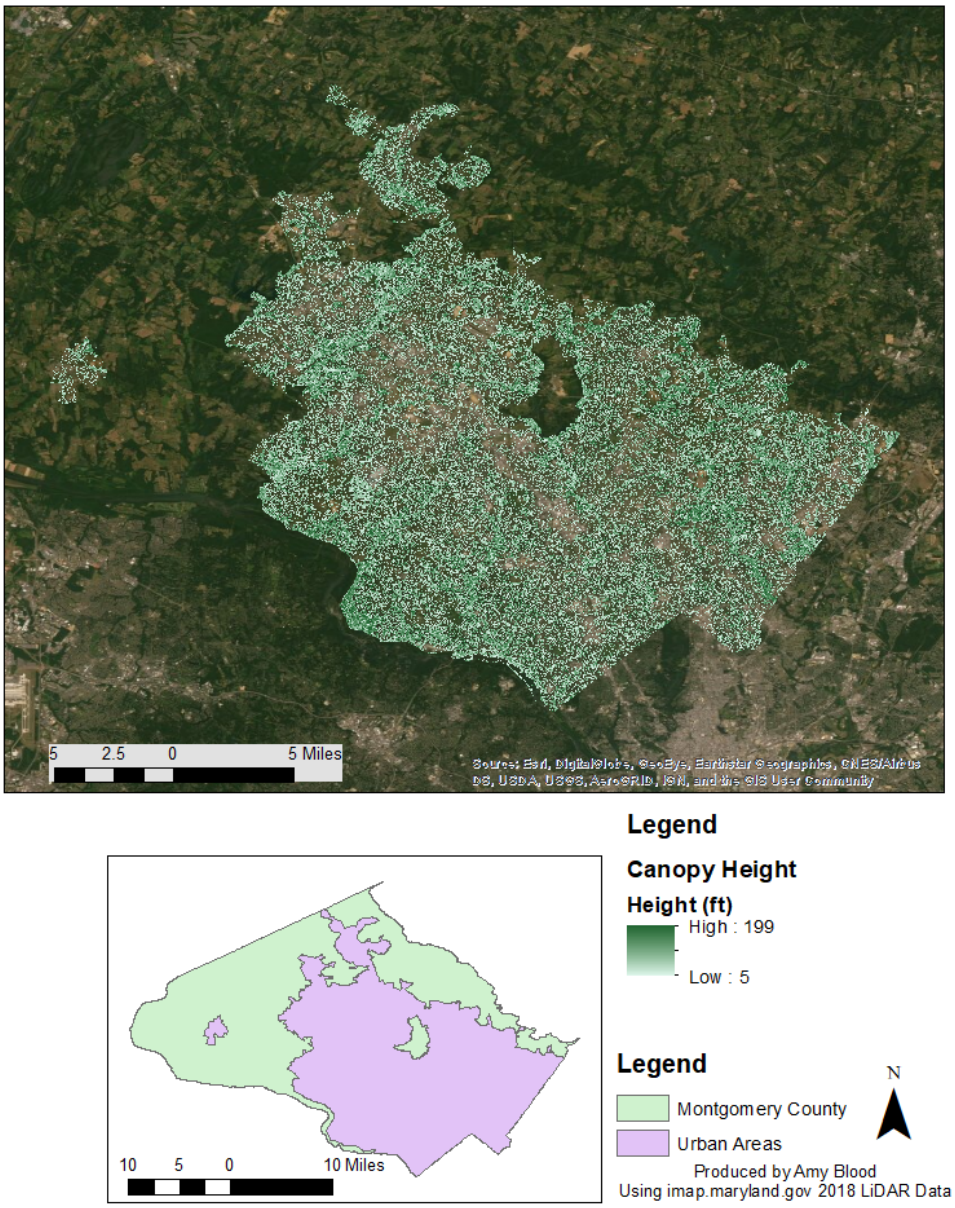


Figure 27. Canopy Height Model for Urbanized Portions of Montgomery County

Figure 28. Tree delineation examples within the study area. The delineation in the left image was completed manually, using orthoimagery and lidar data to define tree canopies. The right image was completed with LiDAR data, using the LidR package in R Studio.

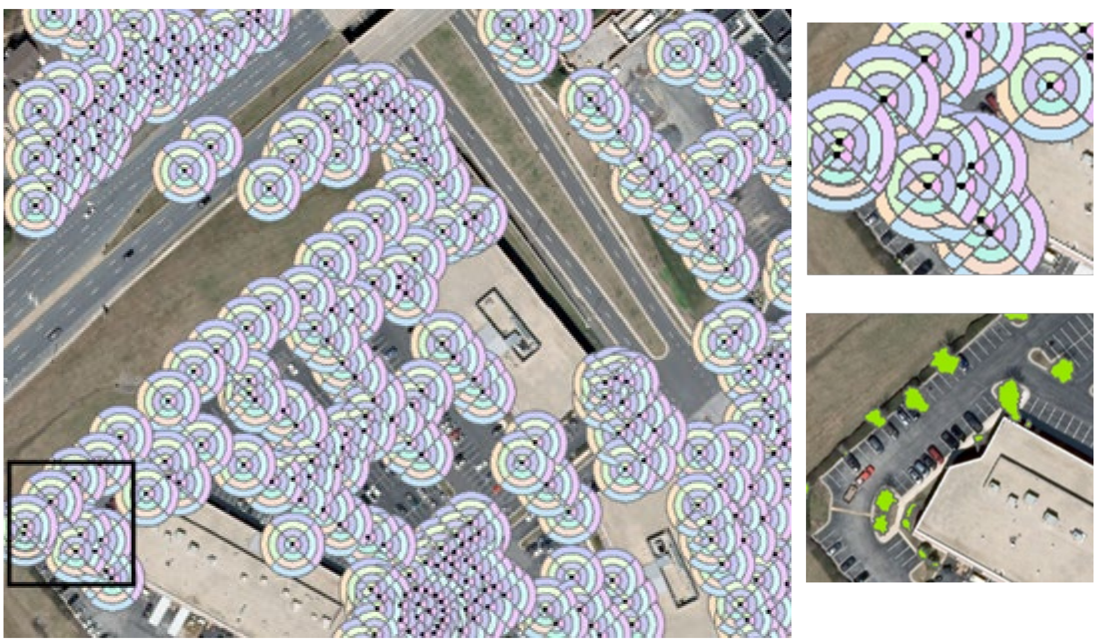


Figure 29. Left, directional buffers in a subset of the study area. Right, the trees in this image can be identified as being on the edge of an impervious area or directly within the impervious area due to the division of buffers into quadrants.

6 CONCLUSIONS AND RECOMMENDATIONS

This study investigated separate components of the hydrologic cycle for trees of three canopy types. The study provided insight on how trees can impact each component, and tested methods for measuring these impacts. In addition, the study used available geospatial data to test whether an Ecohydrological Typology for Urban Trees could be feasibly developed. Taken together, the study has some implications for the impacts of trees in the urban environment.

6.1 Important Findings

Taken together, the data suggest that trees of different species and in different settings differ in their impact on the hydrologic cycle. However, the effects of tree setting on runoff depth and transpiration were not statistically significant. Further, the data suggest that an ecohydroloical Typology for urban trees can be developed using available geospatial data. Other key findings are summarized below.

6.1.1 TRANSPIRATION

- Using sap flow as a surrogate for transpiration appears to be a workable and effective surrogate for transpiration on a per-tree basis.
- On a per-tree basis, individual trees have greater transpiration than trees in a closed canopy setting. This result was contrary to the original hypothesis of this project but could be explained by both the scale of the analysis (per-tree versus per-unit area), and the greater degree of sunlight and exposure of these individual trees.
- Transpiration was correlated with micro-climate conditions (reflected in calculated VPD) as anticipated but showed no obvious relationship to soil moisture.
- Tulip poplars and red maples were both present at the Closed Canopy site. In season 1, the monitoring period began in June, while it began in April in Season 2. In Season 1, tulip poplars had a higher seasonal transpiration rate than red maples, but the transpiration rates for red maples were higher in Season 2. This result lends support to the hypothesis that tulip poplars have a higher peak transpiration rate, but that red maples have greater seasonal transpiration due to their earlier leaf-out period.
- Although this study allowed for comparison between individual trees in each setting, it did not compare the overall volume of transpiration across each study site. Ongoing work at the University of Maryland is comparing transpiration on a pare are basis across each study site.
- The initial approach outlined in the study was to estimate the area of sapwood using dye to separate sapwood from hardwood, but the dye contrast was not visible on these trees. A literature method was successfully used as a surrogate to convert observed sap flux to whole tree water use.

6.1.2 INTERCEPTION

- After separating storm events and directly comparing runoff observed over the canopy to runoff observed outside of the canopy, it appears that the tree canopy, regardless of setting intercepted about 22% of rainfall during the growing season, and about 9.6% outside of the growing season.

- While the actual depth of interception was significantly correlated with rainfall depth, the fraction of interception appeared to be relatively consistent across storm events.
- Some error was inherent in these measurements, largely due to variations in rainfall measurement. Sources of error included storm bursts that fell on only a portion of the site, and rainfall concentrating in the tree canopy, such that the gage below the tree reflected either a greater or lesser amount than the actual amount of interception provided. The results did not eliminate all values with error to avoid bias but did eliminate extreme outliers.
- It was not possible to determine from the data how much of the rainfall intercepted ultimately reached the soil as stem flow.

6.1.3 INFILTRATION AND RUNOFF

- Runoff and infiltration were successfully calibrated observed soil moisture using a continuous (15-minute) Green-Ampt soil moisture model calculator.
- While results were highly variable due to effects such as season, storm intensity, initial soil moisture and storm length, the results are generally consistent with both the CBP urban tree canopy credits, although a lower Phosphorus concentration for the Closed Canopy setting suggests that the loading rate may be lower that Trees Over Turf.
- The curve numbers observed for events with greater than 2.5" of throughfall suggest that the model results were generally consistent with the Water Balance model used to develop the CBP tree canopy credits.
- The original intent of this study was to use available literature values to estimate a single value for Saturated Conductivity (K), but the model results were not consistent with observed soil moisture. Consequently, K was used as a model calibration parameter.
- One potential issue with the modeling results was that soil moisture was measured only in the first 30 cm and appeared to be homogenous over that depth. This assumption
- Although the study period included several storm events, capturing events that were of sufficient length, had rainfall data both under and outside the canopy, and had available soil moisture data somewhat limited the pool of events. This is generally a challenge of field storm-based studies, and this study relied on several pieces of data to adequately characterize each storm.

6.1.4 ECOHYDROLOGICAL TYPOLOGY

- Sufficient data were available from geospatial data sources to adequately characterize the tree canopy.
- Key ELCs could be successfully extracted from available data.
- Individual trees were identified using automated methods and were similar to results from hand-delineation.
- It was possible to identify buffers radiating from the center of a tree and define its setting based on characteristics in the area surrounding it.

6.2 Recommendations and Next Steps

This study provided the foundations to better characterize the water balance in urban settings, characterize these trees based on available geospatial data, and understand how trees function differently based on their setting or canopy type. Future studies could expand on this initial concept through further monitoring, research and analysis:

6.2.1 TREE CANOPY CHARACTERIZATION

The work completed as a part of this project did not involve characterizing the tree canopy, but later work by the University of Maryland included a tree inventory at each site. This work is setting the groundwork to allow researchers to compare transpiration rates on a per-area basis between each setting.

6.2.2 SOIL PROFILE INFLUENCE

This study evaluated soil moisture in the first 30 cm of soil, and runoff processes are influenced by soil characteristics at this depth. However, it was unclear from the available soil information if the wetting front continued to move deeper through the soil. In addition, while the soil appeared to be uniform within the first 30 cm it was unclear if the characteristics of the soil changed below this depth, possibly influencing the rate of infiltration, perhaps through an impermeable layer. Second, while we saw a general pattern of soil moisture decreasing between storm events and increasing during these events, it was unclear if tree roots drew from deeper than the 30 cm depth, and to what extent this transpiration affected soil moisture.

In addition, while the study was useful for comparing soil moisture, and consequently runoff, between the three different tree canopy types, it would be useful to monitor a "turf only" plot to act as a baseline. Paired moisture and rainfall data between tree canopy sites and turf would allow for a direct measure of runoff reduction.

Future studies could investigate movement through the soil by installing moisture probes at multiple depths, to explore water movement deeper through the soil profile.

6.2.3 RAINFALL/THROUGHFALL MEASUREMENT

Two potentially interesting future questions are in regard to throughfall are the variability of throughfall measurement and the potential contribution of stemflow. One potential future study could evaluate this variability by comparing observed throughfall data from multiple locations under the canopy of a single site and measuring stem flow. It could help to determine an ideal monitoring setup for measuring interception.

6.2.4 MORE DETAILED SOIL MOISTURE/TRANSPIRATION MODEL

Although VPD had a clear impact on transpiration, the results were not as clear for soil moisture. Using data from this study, a more detailed model that evaluates transpiration as a function of both variables and considers these values as a time series could help inform soil moisture models.

6.2.5 ADDITIONAL STORM DATA

Even though this study had a large number of storm events, only between eight and twelve (depending on the canopy type) could be used to estimate runoff depth. The storm events observed were variable in terms of storm intensity, length, pre-existing soil moisture, and the same events were not used at each location. Supplementing these data would help to better inform the initial findings of this study.

6.2.6 EFFECTS OF FOREST WITH A MORE ROBUST UNDERSTORY

The Closed Canopy forest observed in this study had very little understory, and similar organic matter to the other two settings. Studying a "higher quality" forest patch with a greater degree of soil organic matter and more complex understory would add to the scope of this original study. Further, models assume an effect of urban trees on the underlying soils, but more information is needed to characterize differences in the soil profile associated with different tree typologies.

6.2.7 ECOHYDROLICAL TYPOLOGY FOR URBAN TREES

The results from this study suggest that it is feasible to develop an urban tree typology relying primarily on remotely sensed data. Ongoing work at the University of British Columbia is continuing to develop more extracted data layers at the scale of Montgomery County, and to use statistical modeling techniques to segregate trees into distinct typology classes.

6.2.8 FURTHER HYPOTHESES

Recommended future hypotheses include:

1. Do urban trees draw transpiration from the deep soil profile during drier periods, such that the water balance should account for this additional input? Are we able to develop a statistical model based on transpiration, soil moisture and environmental conditions that predicts soil moisture?
2. How are urban soils impacted by trees in the urban environment, and do current models adequately capture these impacts?
3. Is runoff depth from turf different than runoff from urban trees in various settings for storm events of similar depth, intensity and soil moisture conditions?
4. Do "high quality" forest patches, with management to improve the understory, soil conditions and complexity perform better than closed canopy forest patches of lower quality?
5. Can the steps used to develop an Ecohydrological Typology completed in this study be employed to classify trees in Montgomery County into distinct typologies and to create county-wide extracted datasets?

7 REFERENCES

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