# Stormwater Goes Green:

## The benefit and health of trees in green stormwater infrastructure


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**Forester University Webinars**

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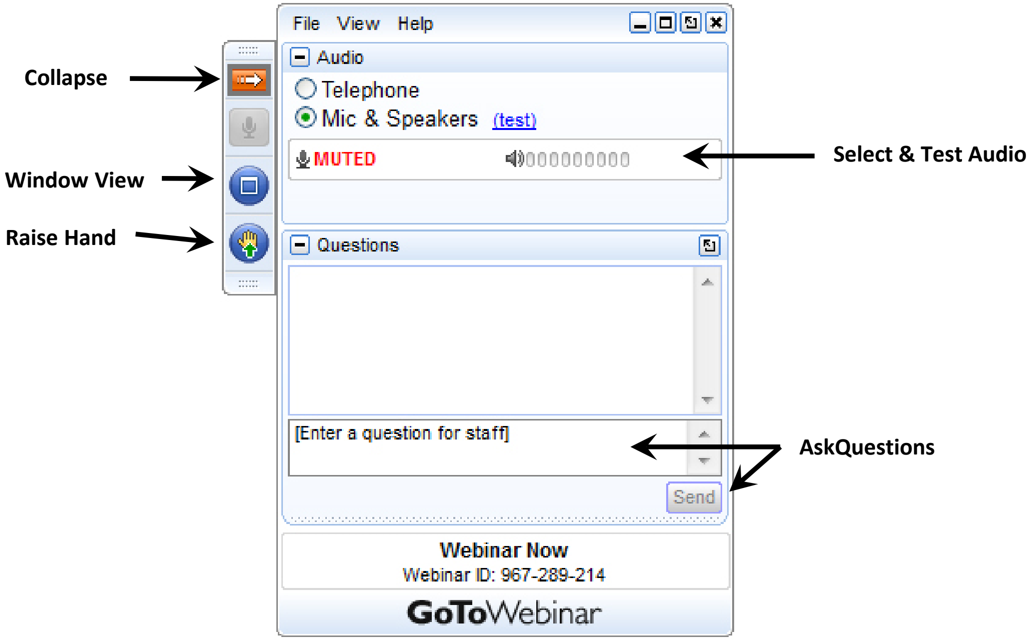


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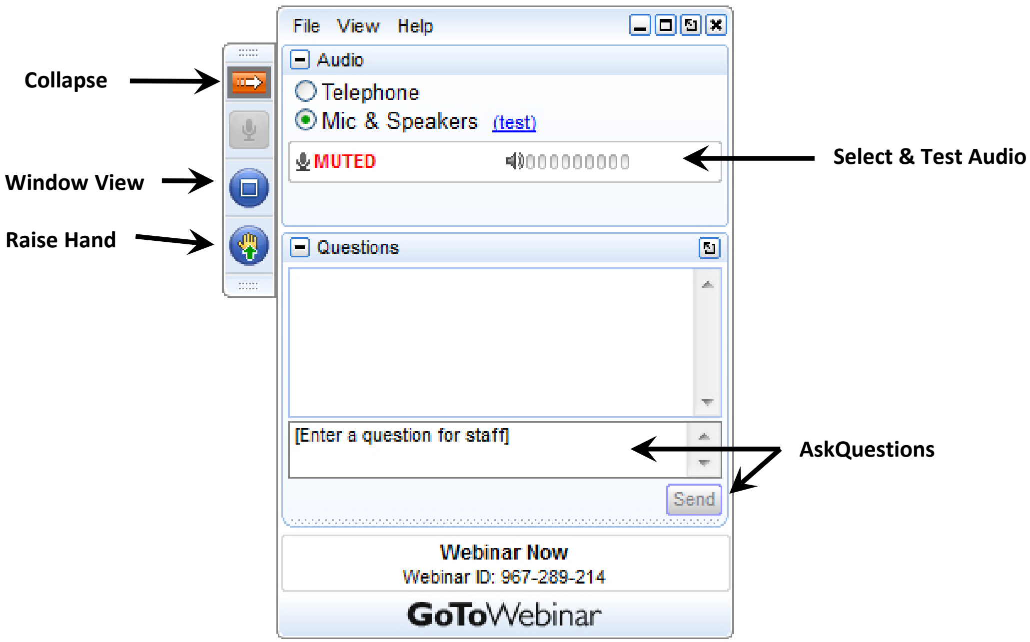


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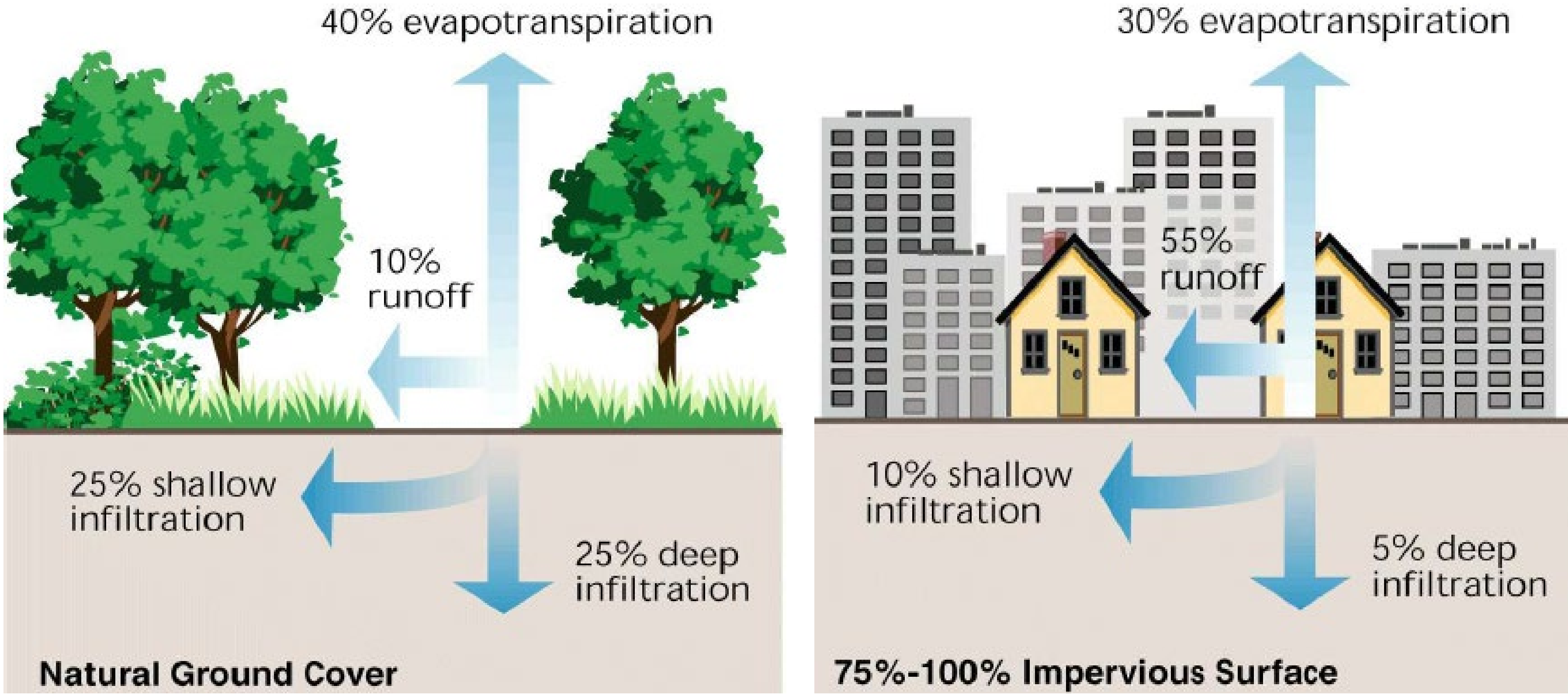
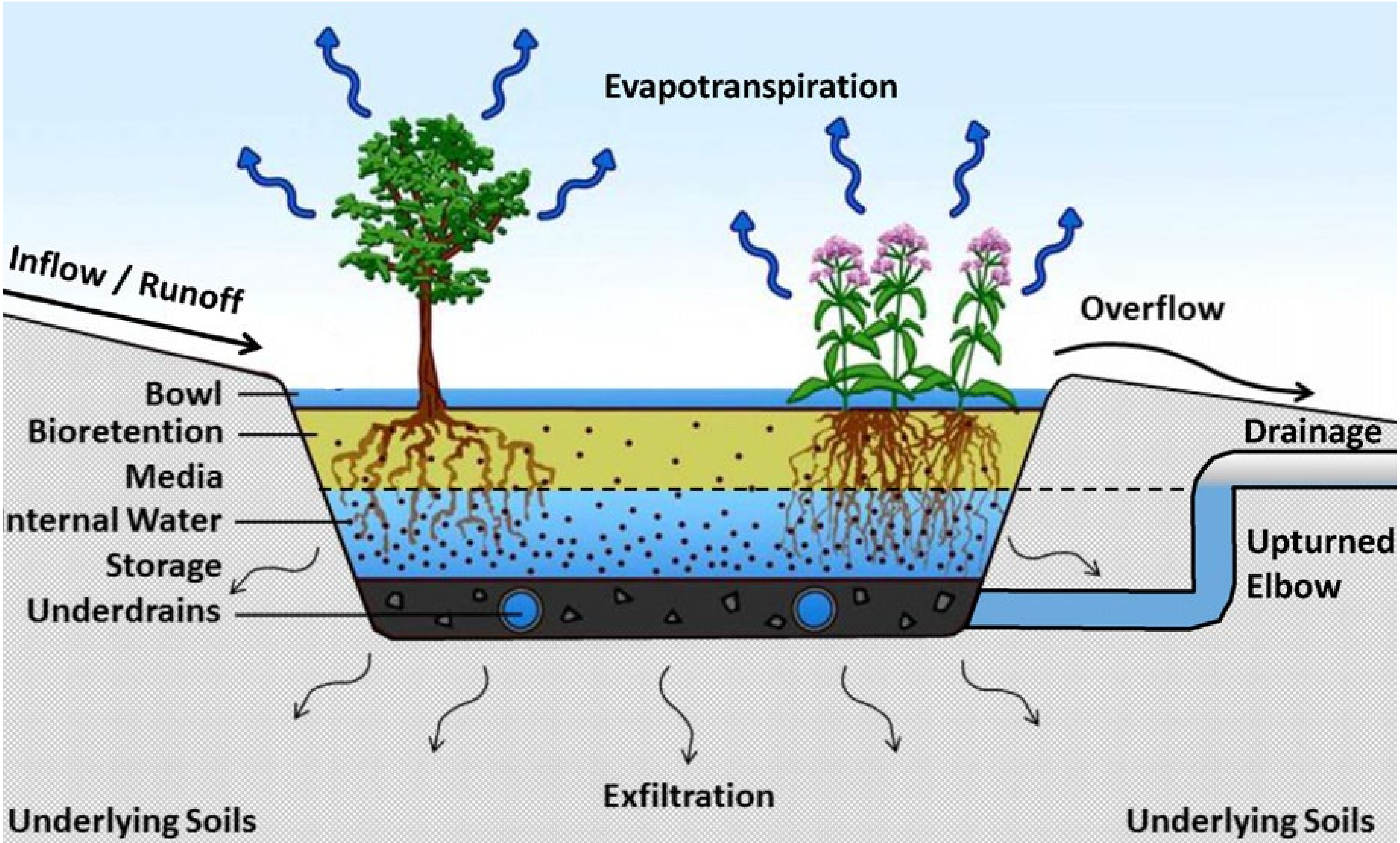
# Urban Stormwater Challenges



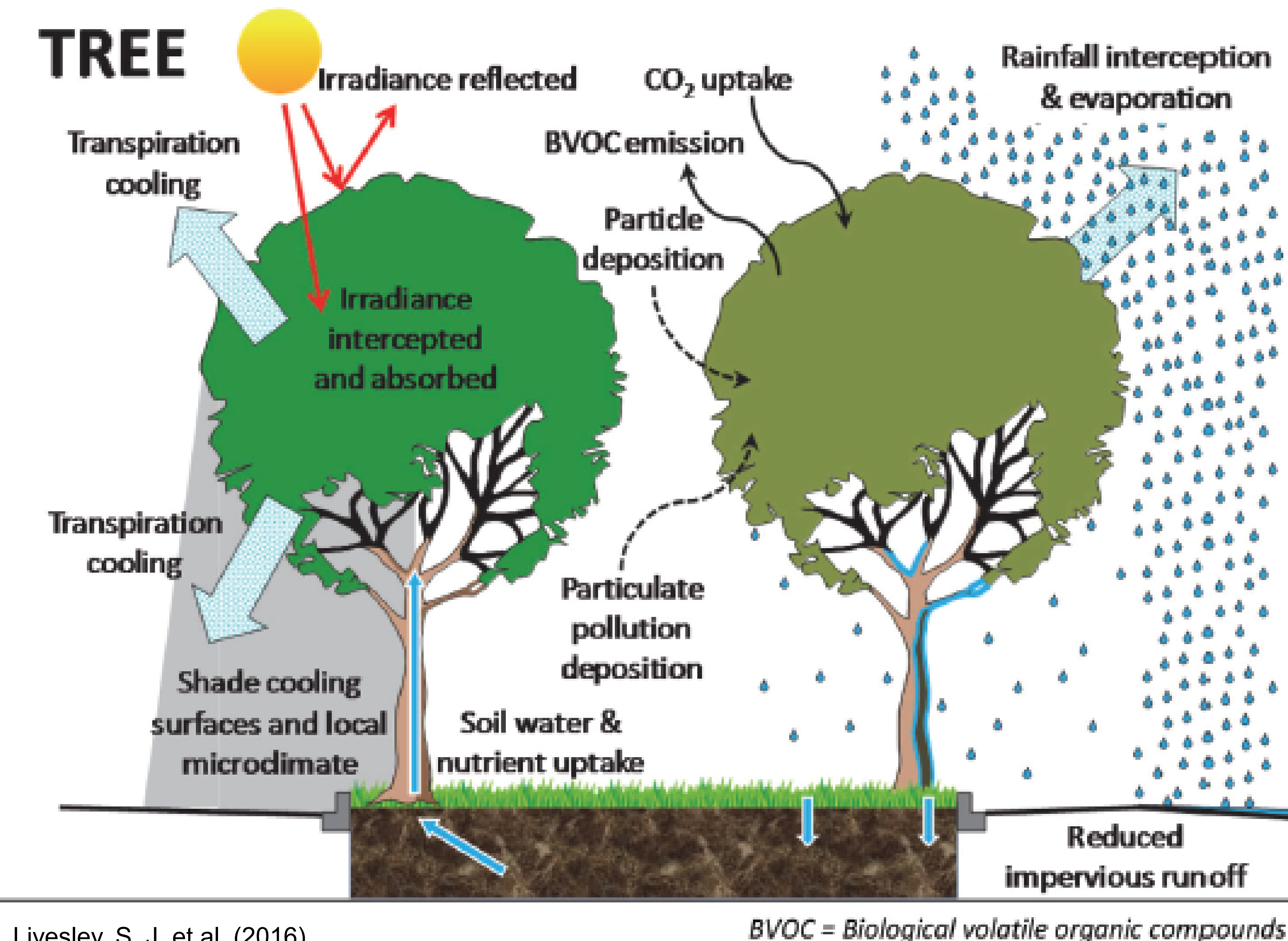

- Impervious surfaces limit infiltration, increase runoff quantity delivered to receiving waters, leading to degraded stream conditions
- Pollutants associated with urban areas (sediment, nutrients, heavy metals) impact chemistry and aquatic ecosystems of receiving waters

# Bioretention Practice: Overview

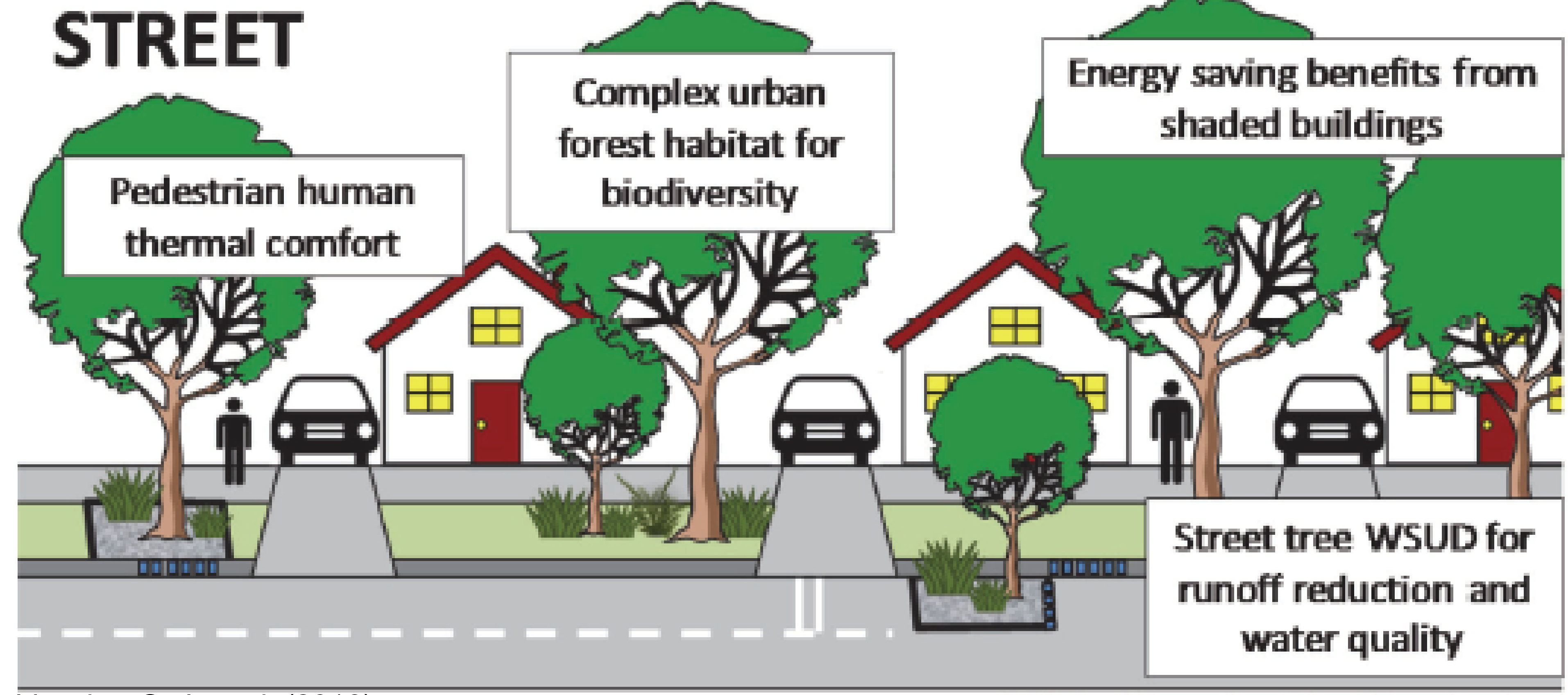


# Benefits and Treatment Mechanisms

- Versatile design
- Aesthetic value
- Volume/Peak Flow:
  - Infiltration
  - Temporary storage
  - Exfiltration/ET
- Pollutant removal:
  - Filtration
  - Sedimentation
  - Soil adsorption
  - Plant and microbial uptake

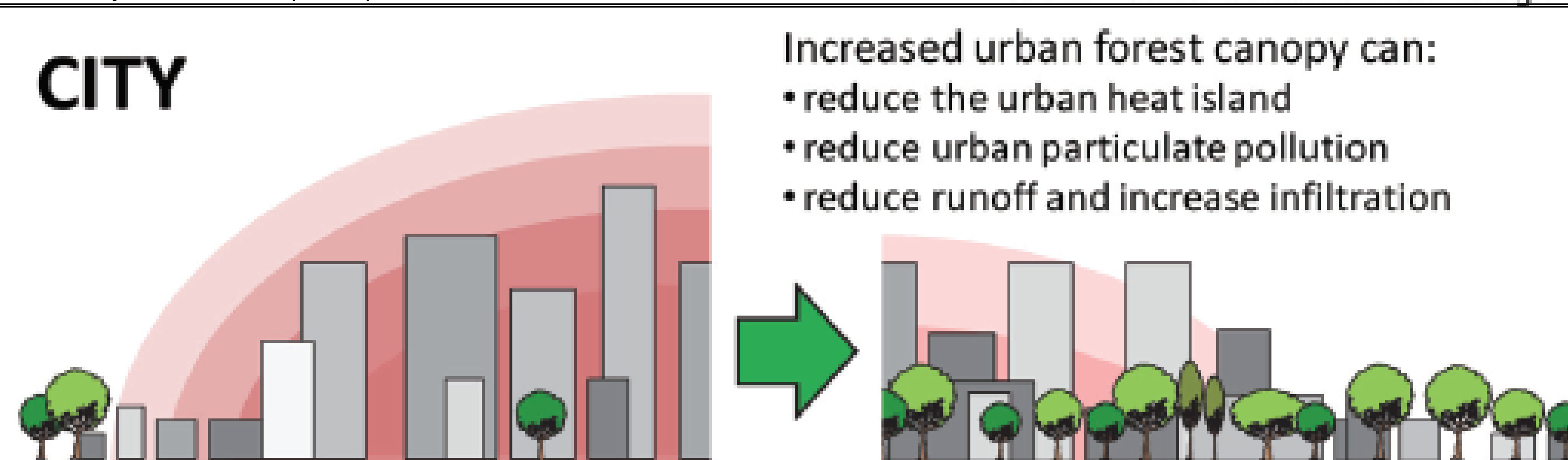



Livesley, S. J. et al. (2016)




Livesley, S. J. et al. (2016)

*WSUD = Water Sensitive Urban Design*



# Knowledge Gaps

- Many studies are limited to grasses, shrubs, and sedges, leaving the need to explore other plant types in bioretention
- Few studies have explored the specific role of trees in bioretention
- Very little research has produced guidance for tree species selection based on physiological aspects that may account for performance contributions

# Research Overview

## Study 1

Field health survey of trees in existing bioretention practices in Tennessee and North Carolina

## Study 2

Controlled experiment on the performance contributions of trees in bioretention mesocosms

## Study 3

Field-scale study of two suspended pavement systems designed to function as bioretention practices

## Study 4

In-situ study of the effect of design strategies and meteorological parameters on tree transpiration in bioretention suspended pavement systems

# **Study 1:**
# The Health of Trees in Bioretention: A Survey and Analysis of Influential Variables

Tirpak, R. A., J. M. Hathaway, J. A. Franklin, and A. Khojandi (2018). "The Health of Trees in Bioretention: A Survey and Analysis of Influential Variables". Journal of Sustainable Water in the Built Environment, 4(4), 4018011.

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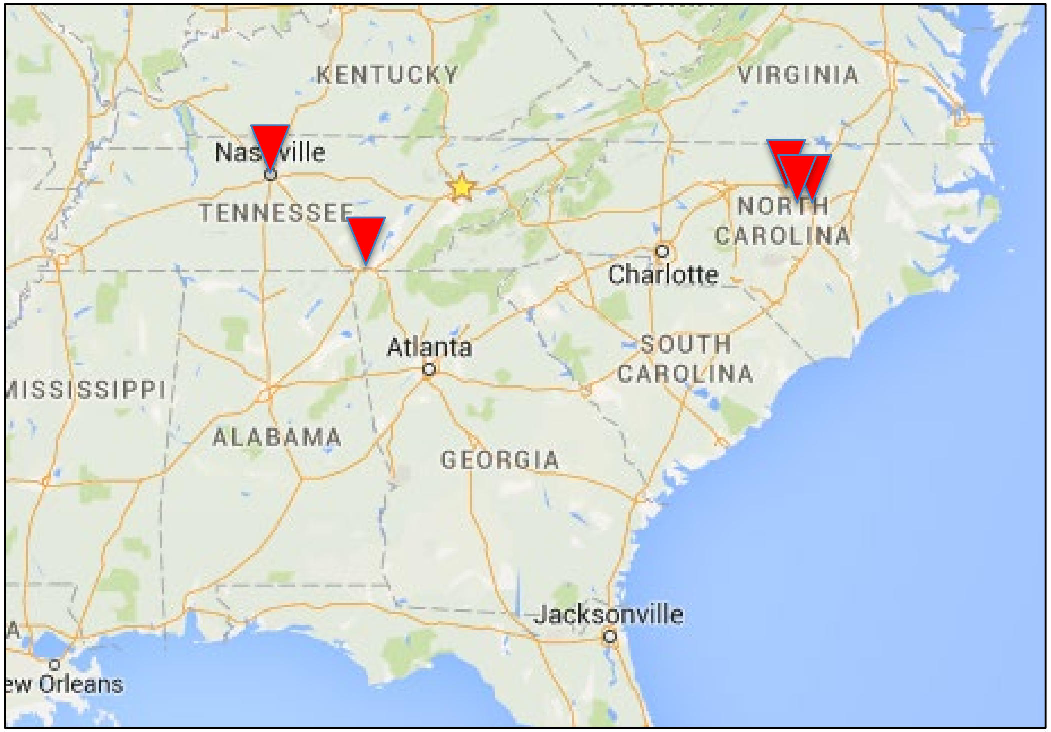
# Bioretention Tree Health Surveys

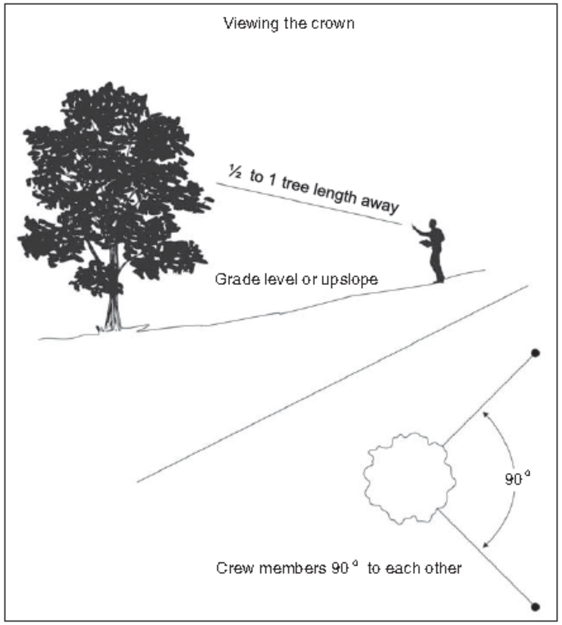
- June-August ‘15
- 38 practices
- 97 trees from 22 species
  - Six species accounted for ~75% of total



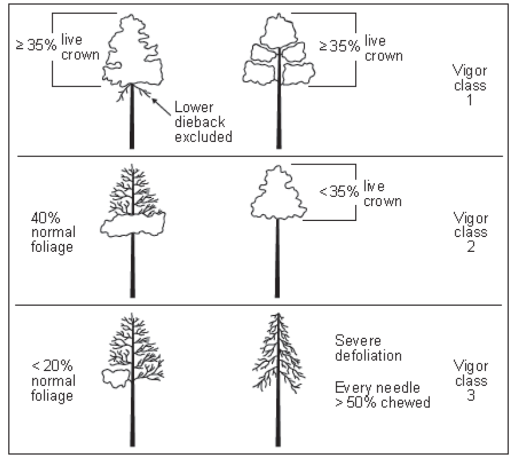




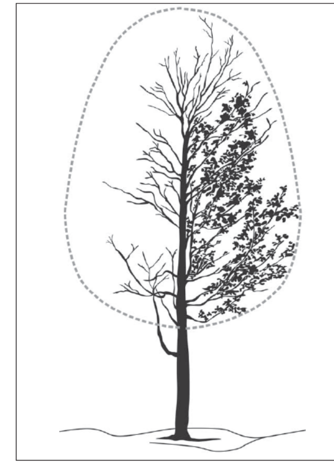
# Crown Condition Indicators



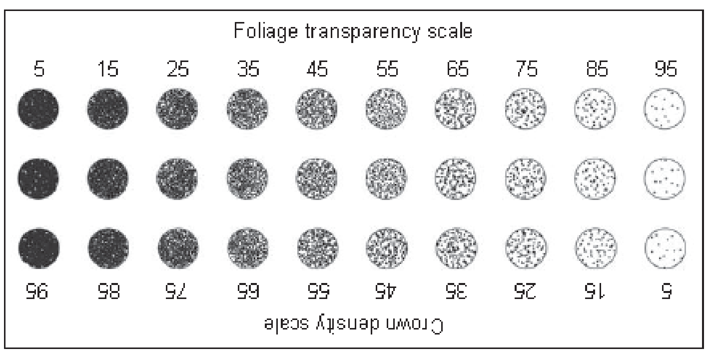

Rating Crown Condition Indicators




Vigor Class

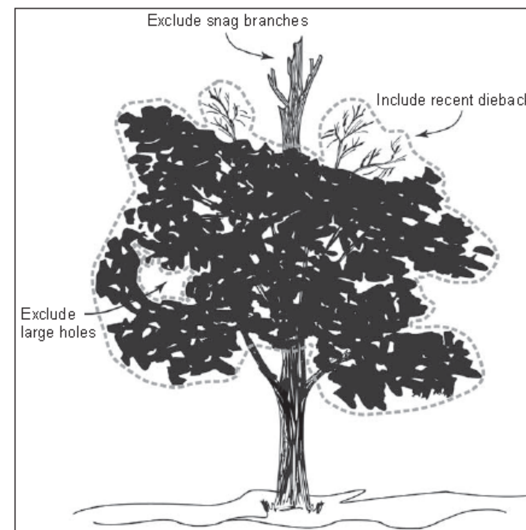


Crown Density




Density/Transparency Scale

Foliar Transparency




Crown Dieback

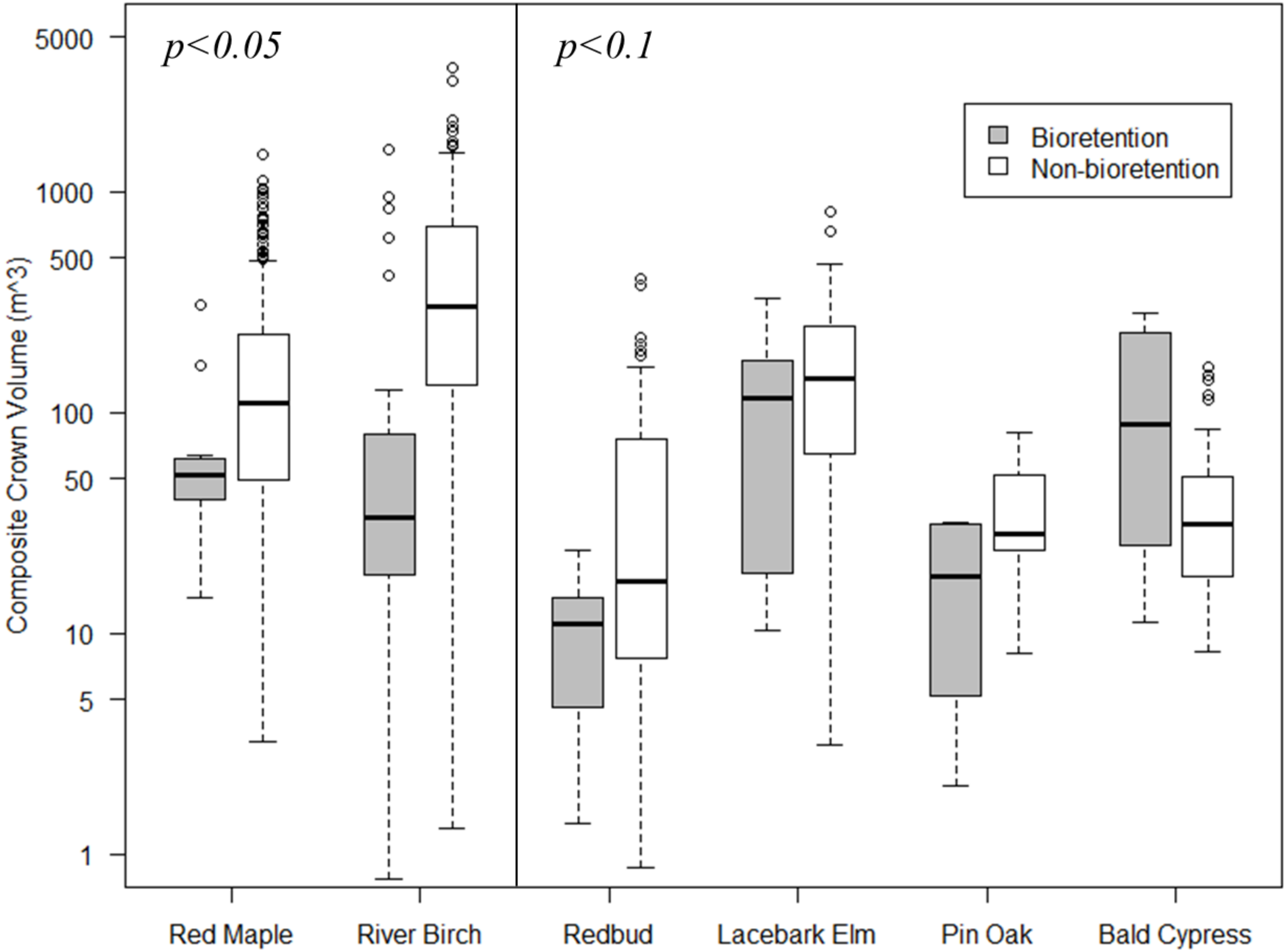
# Composite Crown Indicators (CCI)

- Tree health based on 3D crown shape:
  - Crown Volume $$CCV = \left(0.5\pi R^2 (CL)\right)\left(\frac{CDEN}{100}\right)$$
  - Crown Surface Area $$CSA = \frac{4\pi CL}{3R^2}\left[\left(R^2 + \frac{R^4}{4CL^2}\right)^{1.5} - \left(\frac{R^4}{4CL^2}\right)^{1.5}\right]\frac{CDEN}{100}$$
- **Larger CCI Values = Increased Tree Health**

Zarnoch et al. (2004)

# How does the health of bioretention trees compare to other urban trees?

# Bioretention vs. Non-bioretention Trees



# Comparing Tree Health

- Many species were *less healthy* in bioretention
- Incompatibility with species-specific growing preferences for soil moisture, texture, etc.

| ***Species*** | ***Soil pH*** | ***Saturated or very wet soil*** | ***Moist, well-drained soil*** | ***Occasionally dry soil*** | ***Very dry soil*** |
|---|---|---|---|---|---|
| Bald Cypress | 4.5-6.0 | | | | |
| Pin Oak | 4.5-6.5 | | | | |
| River Birch | 3.0-6.5 | | | | |
| Red Maple | 4.7-7.3 | | | | |
| Redbud | 5.0-7.9 | | | | |
| Lacebark Elm | 4.8-7.0 | | | | |

Bassuk et al. (2009)

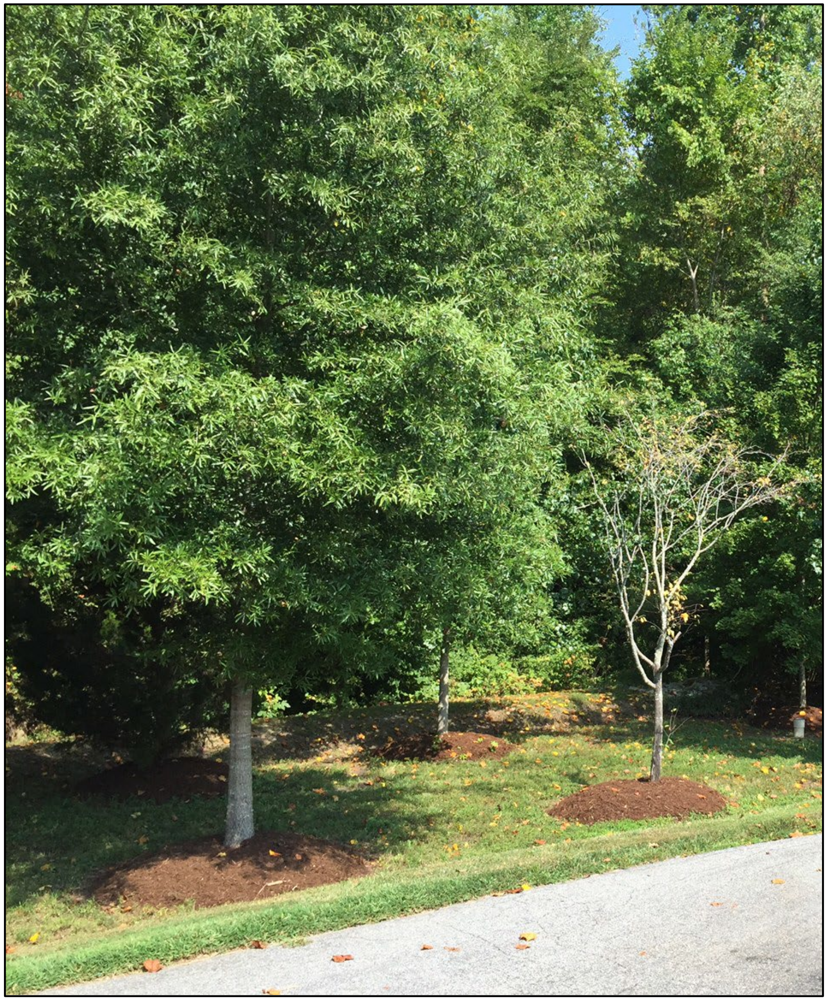
# Comparing Tree Health

- **Eastern redbud:** not found in sandy soils
- **River birch:** prefer tight clay soils, high soil moisture
- **Pin oak:** found in heavy-textured, poorly drained soils
- **Bald cypress:** best growth in moist, fine sandy loam soils without competition

# What bioretention parameters influence tree health?

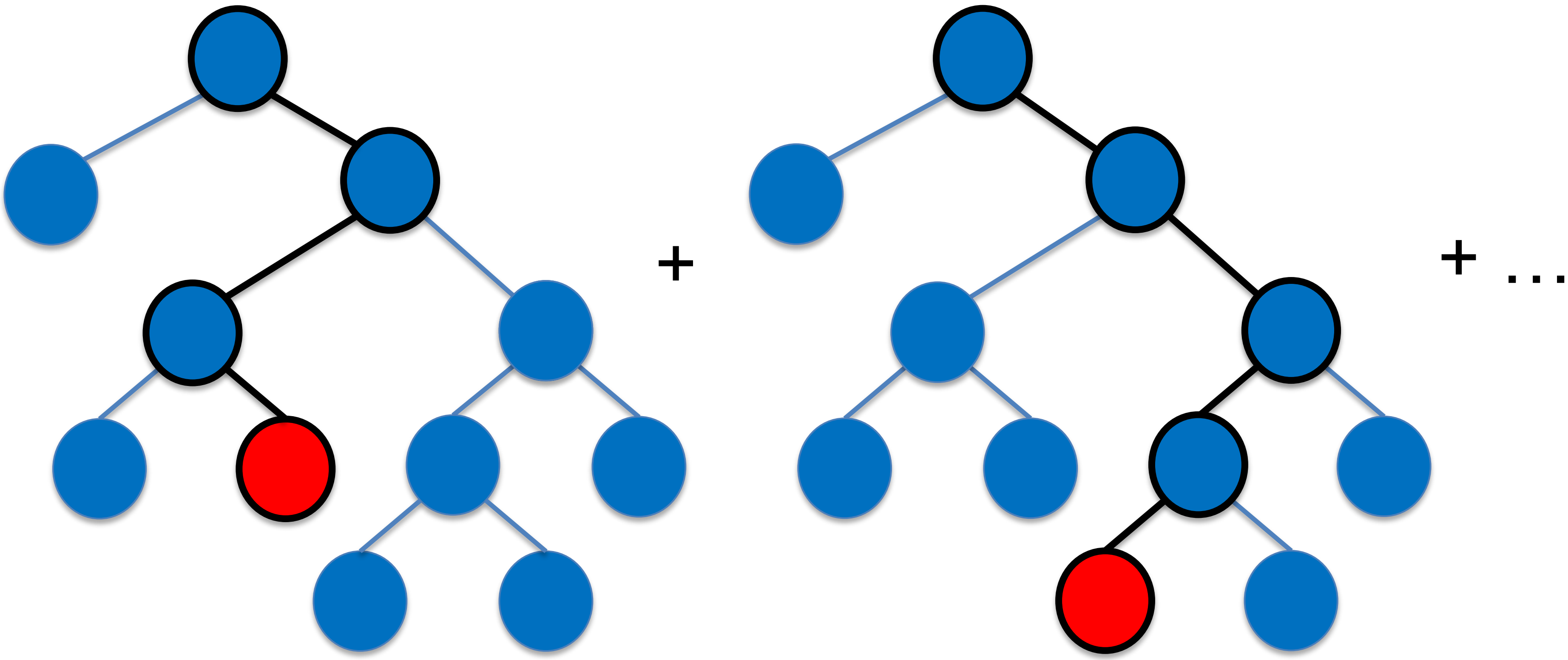
# Factors Influencing Health

- Species selection
- Soil pH
- Soil Chemistry
  - Nutrients, metals
- Soil Composition
  - % Sand, % Fines, OM
- Bioretention Design
  - Surface Area
  - Tree planting location
  - Ponding Depth



# Random Forest Algorithm

- Ensemble learning-based regression technique using numerous decision trees



# High-Importance Design Parameters

| *Category* | *Predictor Variable* | *Comments* |
|---|---|---|
| **Bioretention Media Composition** | Fines (%) | Reinforces findings in tree health comparison study; media should align with species-specific habitat preferences |
| | Sand (%) | |
| | Organic Matter (%) | Influences soil fertility, structure; OM standards vary |
| **Bioretention Media Chemistry** | Buffer pH | Controls fluctuations in soil pH which could impact root function; influences nutrient availability in media |
| | Copper | Micronutrient; deficiency leads to crown defoliation and dieback (other micronutrients are also key) |
| | Potassium | Vital to plant functions (photosynthesis, water regulation, cell expansion); required in large amounts |
| **Tree Selection and Planting** | Planting Location | Should reflect tree tolerance to inundation |
| | Species Selection | Species should be tolerant of bioretention environment |

# Tree Health Survey Conclusions

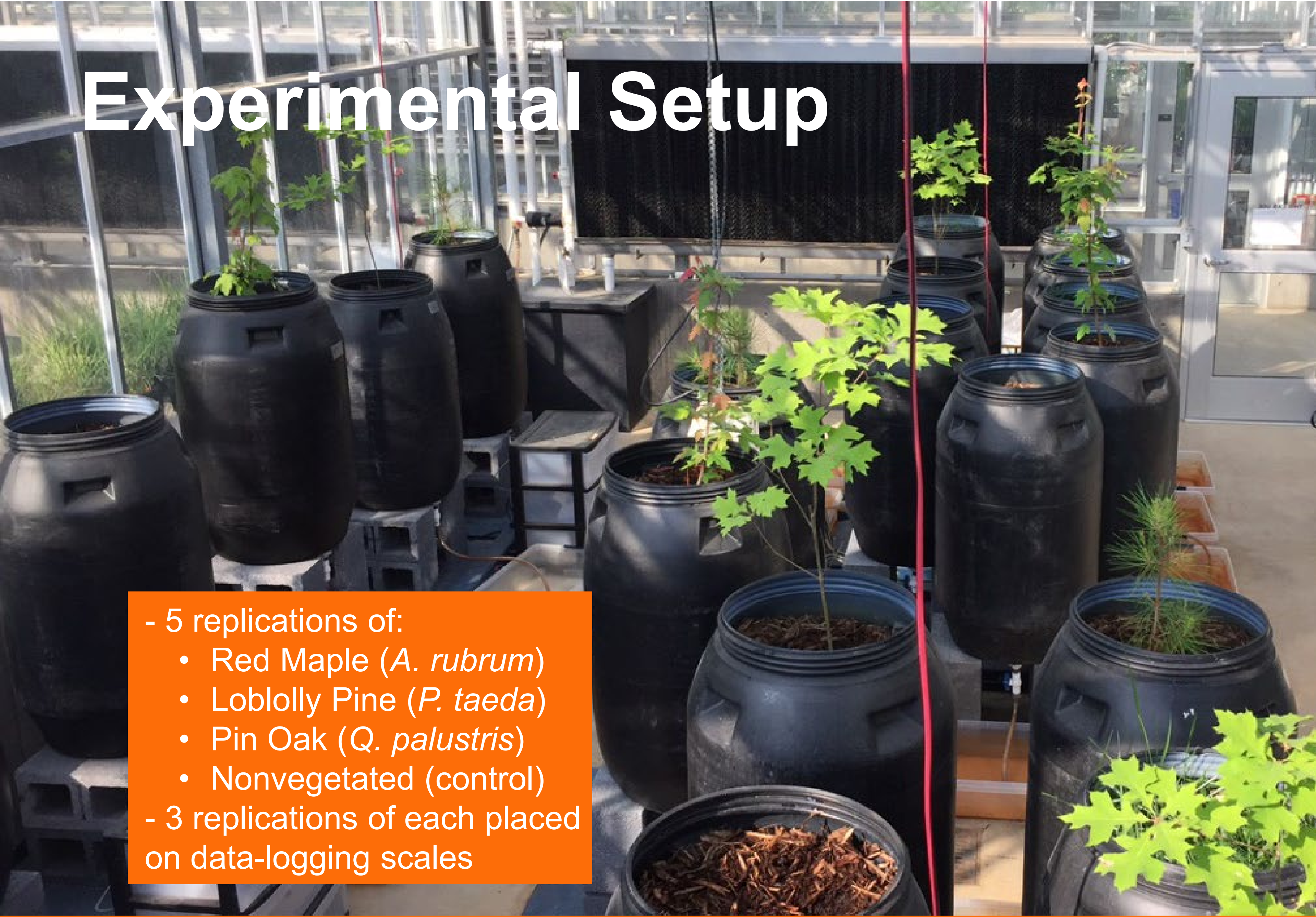
1. Trees should be selected based on their ability to tolerate the unique conditions found in bioretention practices. Species-specific preferences for growing conditions should be considered during selection.

2. Species selection should be guided by analysis of bioretention media composition, prioritizing high-importance parameters.

**Study 2:**

Investigating the Hydrologic and Water Quality Performance of Trees in Bioretention Mesocosms

# Experimental Setup



- 5 replications of:
  - Red Maple (*A. rubrum*)
  - Loblolly Pine (*P. taeda*)
  - Pin Oak (*Q. palustris*)
  - Nonvegetated (control)
- 3 replications of each placed on data-logging scales

# Mesocosm Components

# Synthetic Stormwater Application

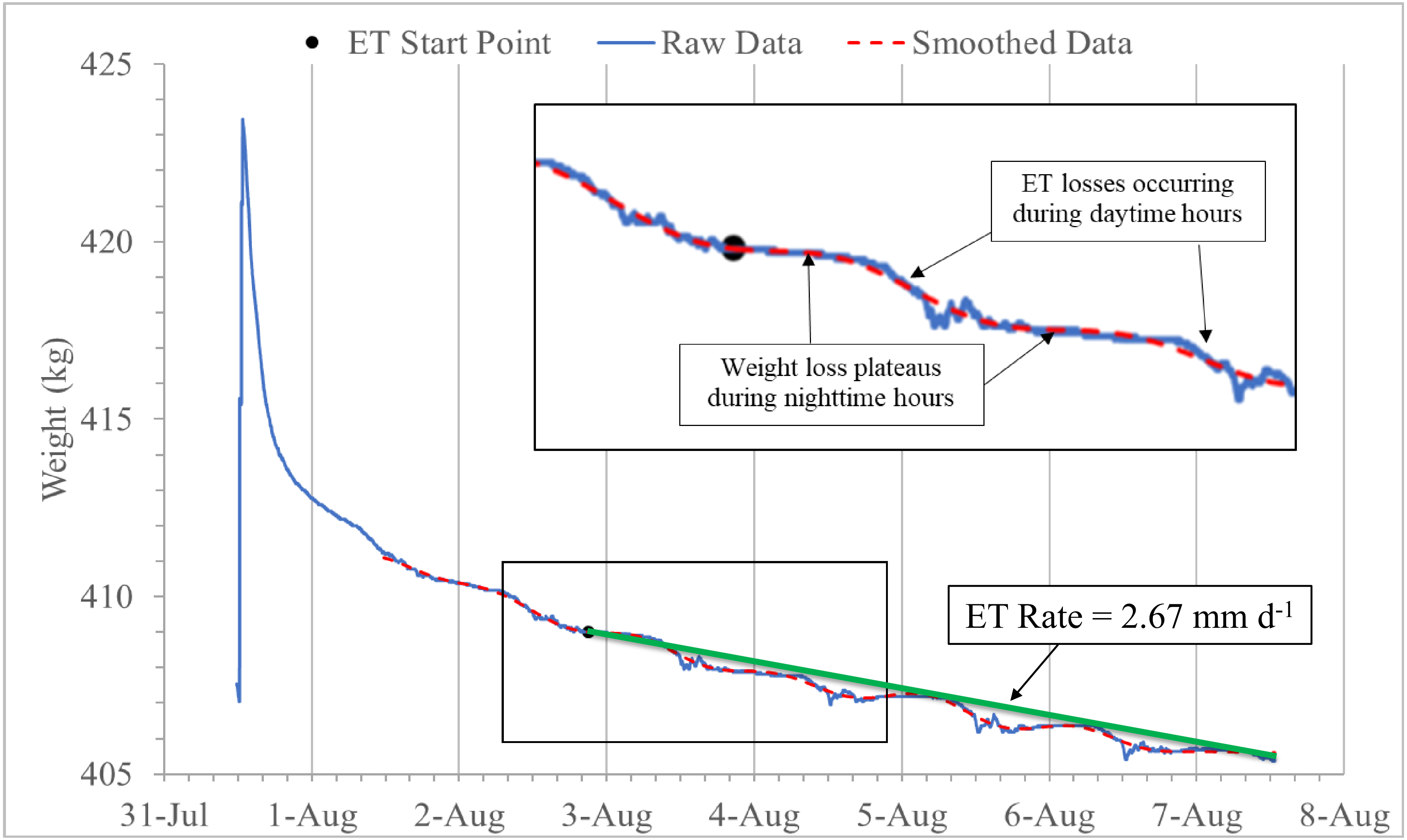
- Sources of TSS, nutrients, metals added to continuously mixed tank (Bratieres et al., 2008)
- Dosing based on 30 years of rainfall data in Knoxville, TN
  - 0.2" median storm event, 80 events/year, 15:1 loading ratio
- Applied over a 14 week period (June-October 2017)
- ET analyzed during week-long dry periods after watering sessions (6 events)

# Synthetic Stormwater Composition

| Pollutant | Mean Conc. (CV, %) | Source |
| --- | --- | --- |
| TSS (mg $L^{-1}$) | 75 (26.7) | Stormwater sediment |
| $NH_4^+$-N (mg $L^{-1}$) | 0.39 (135.7) | $NH_4CL$ |
| $NO_x$-N (mg $L^{-1}$) | 3.62 (4.0) | $KNO_3$, other N sources |
| $PO_4^{3-}$ (mg $L^{-1}$) | 0.17 (85.1) | $KH_2PO_4$ |
| Cu (µg $L^{-1}$) | 67 (24.1) | Standard Cu solution |
| Pb (µg $L^{-1}$) | 51 (46.1) | $PbNO_3$ |
| Zn (µg $L^{-1}$) | 206 (16.0) | Standard Zn solution |
| Cr (µg $L^{-1}$) | 18 (30.8) | Standard Cr solution |
| Mn (µg $L^{-1}$) | 201 (3.8) | Standard Mn solution |
| Fe (µg $L^{-1}$) | 654 (30.9) | $FeSO_4$ |
| Ni (µg $L^{-1}$) | 23 (9.1) | Standard Ni solution |
| Cd (µg $L^{-1}$) | 5 (22.9) | Standard Cd solution |

Target levels based on typical runoff concentrations presented by Bratieres et al. (2008)

# Scale Data Analysis



# Effect of Tree Species on Water Quality

| Pollutant | Influent Stormwater | Effluent | | | |
|---|---|---|---|---|---|
| | | Nonvegetated | Red Maple | Loblolly Pine | Pin Oak |
| TSS ($mg\ L^{-1}$) | 75±5 | 3±1 | 5±1 | 3±1 | 2±1 |
| $NH_4^+$-N ($mg\ L^{-1}$) | 0.39±0.14 | 0.01±0.00 | 0.01±0.00 | 0.01±0.00 | 0.01±0.00 |
| $NO_x$-N ($mg\ L^{-1}$) | 3.62±0.04 | 0.13±0.03 | 0.12±0.02 | 0.17±0.03 | 0.14±0.03 |
| $PO_4^{3-}$ ($mg\ L^{-1}$) | 0.17±0.04 | 0.06±0 | 0.06±0 | 0.06±0 | 0.06±0 |
| Cu ($\mu g\ L^{-1}$) | 67±4 | 3±0 | 4±1 | 3±0 | 3±0 |
| Pb ($\mu g\ L^{-1}$) | 51±6 | 4±1 | 4±1 | 10±3 | 4±1 |
| Zn ($\mu g\ L^{-1}$) | 206±9 | 42±10 | 36±8 | 35±7 | 40±7 |
| Cr ($\mu g\ L^{-1}$) | 18±1 | 3±0 | 3±0 | 4±0 | 4±0 |
| Mn ($\mu g\ L^{-1}$) | 201±2 | $339±26^{A}$ | $254±26^{B}$ | $184±29^{B*}$ | $254±18^{B*}$ |
| Fe ($\mu g\ L^{-1}$) | 654±54 | 61±15 | 103±32 | 114±28 | 100±27 |
| Ni ($\mu g\ L^{-1}$) | 23±1 | $2±0^{A}$ | $2±0^{A}$ | $8±2^{B}$ | $2±0^{A}$ |
| Cd ($\mu g\ L^{-1}$) | 5±0 | 2±0 | 2±0 | 2±0 | 2±0 |

Note: Significant differences ($p$<0.05) between treatments indicated by different letters and asterisk (*) when necessary.



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# Comparison of ET Rates

| Treatment | Mean ET Rate ±SE (mm $d^{-1}$) |
|---|---|
| Nonvegetated | 2.01±0.10$^{A}$ |
| Loblolly Pine | 2.21±0.12$^{B}$ |
| Pin Oak | 2.19±0.08$^{B}$ |
| Red Maple | 3.22±0.20$^{C}$ |

- Nonvegetated (evaporation only) significantly lower than mesocosms planted with trees ($p$<0.05; $p$<0.1 for pin oak)
- Mean transpiration rates ranged from 0.18 mm $d^{-1}$ (pin oak) to 1.21 mm $d^{-1}$ (red maple), accounting for 8.2-37.5% of ET
- Species differences tied to plant development and growth

# Conclusions

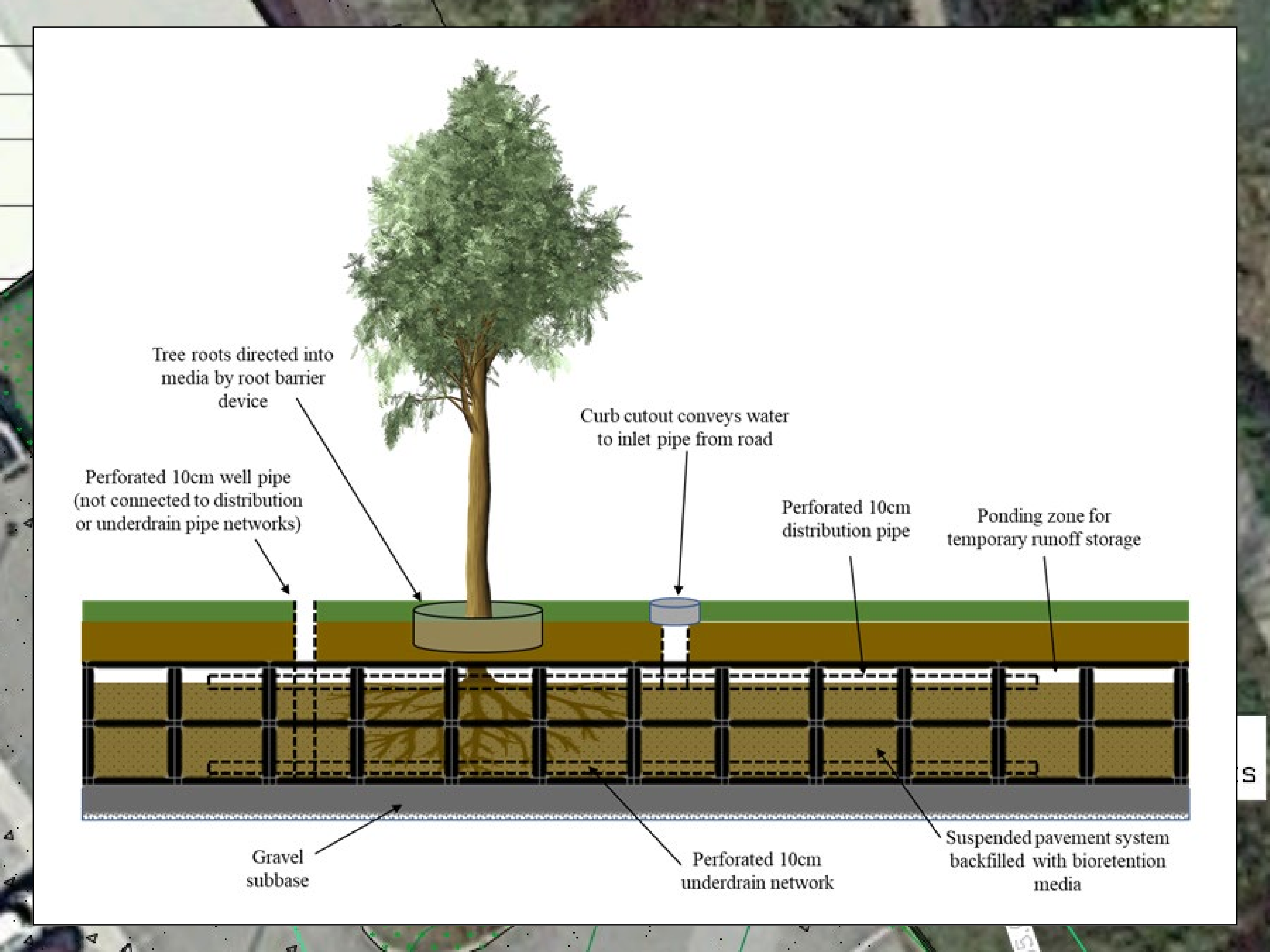
- Differences in water quality performance not significant; attributable to small soil volume occupied by roots of seedlings in the mesocosms
- Daily ET rates significantly higher in treed mesocosms compared to nonvegetated control
  - Highlights the role of <u>transpiration</u> in bioretention hydrology (8.2-37.5% of average daily water losses)
- Highest ET in mesocosms planted with red maple (3.2 mm $d^{-1}$); linked to plant development, canopy size, and growth compared to other species

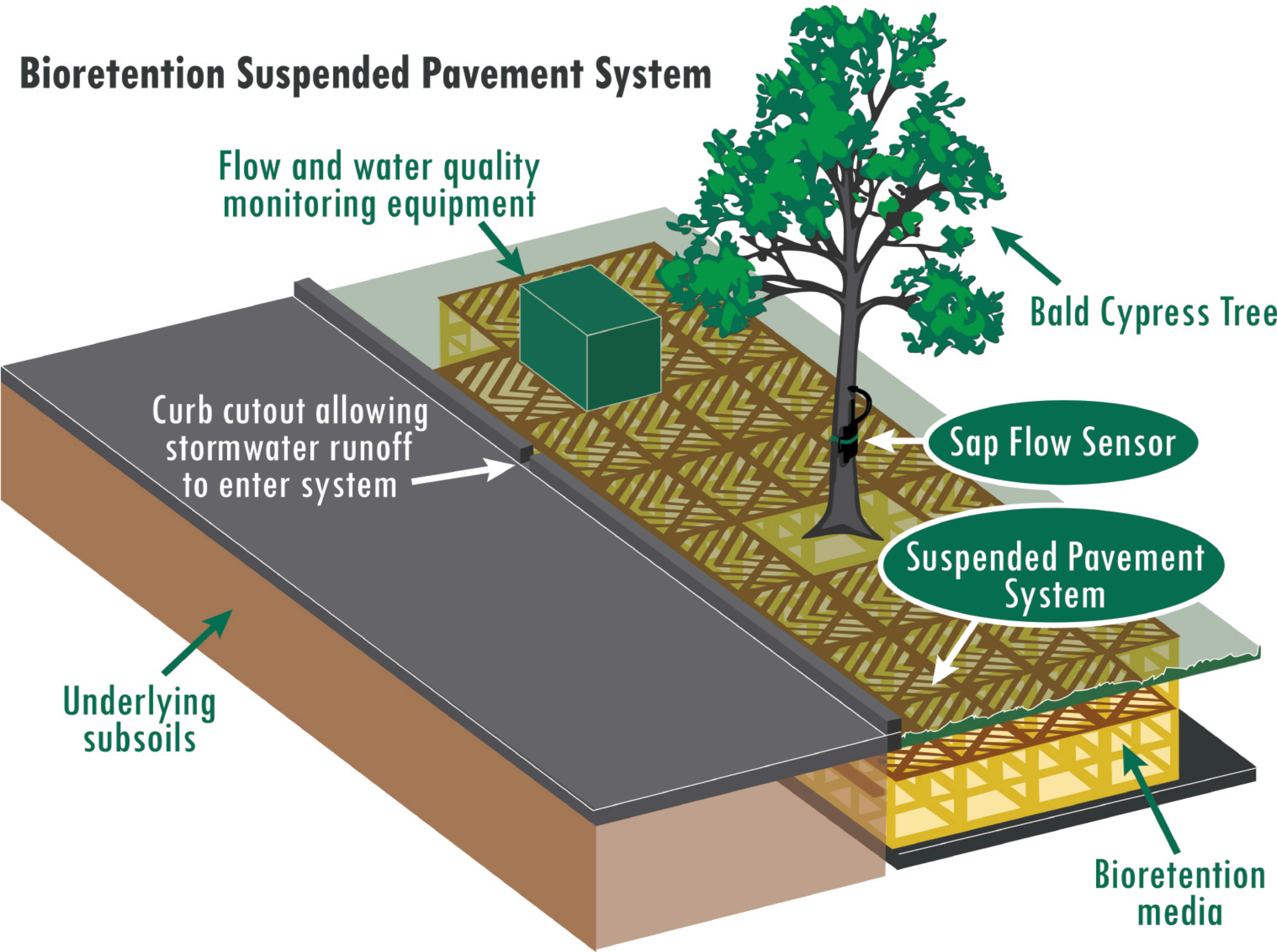
**Study 3:**

# Hydrologic and Pollutant Removal Performance of Suspended Pavement Systems Used for Stormwater Management

# Introduction

- Urban soil conditions present challenges to tree, root growth
  - High compaction, low nutrients, poor aeration (Craul et al., 1985)
- Suspended pavement systems improve root access to air and water in an uncompacted soil matrix; take advantage of limited land availability in ultra-urban landscapes
- Very little research on suspended pavement systems designed as subsurface bioretention to-date
  - Suspended pavement system lined with impermeable membrane in Wilmington, NC (Page et al., 2015)
  - Peak flow rates reduced by 62%; significant pollutant removal
  - Lined system may not be applicable to installations outside research


Tree roots directed into media by root barrier device
Curb cutout conveys water to inlet pipe from road
Perforated 10cm well pipe (not connected to distribution or underdrain pipe networks)
Perforated 10cm distribution pipe
Ponding zone for temporary runoff storage
Gravel subbase
Perforated 10cm underdrain network
Suspended pavement system backfilled with bioretention media


Bioretention Suspended Pavement System
Flow and water quality monitoring equipment
Bald Cypress Tree
Curb cutout allowing stormwater runoff to enter system
Sap Flow Sensor
Suspended Pavement System
Underlying subsoils
Bioretention media

# Site Design Components

| Parameter | North Site | South Site |
|---|---|---|
| Drainage area ($m^2$) | 183.0 | 138.5 |
| Imperviousness (%) | 100 | 100 |
| Design storm event (mm) | 25.4 | 25.4 |
| Treatment surface area ($m^2$) | 22.3 | 27.0 |
| Approx. loading ratio | 8:1 | 5:1 |
| Silva Cell Decks | 28 | 35 |
| Silva Cell Frames | 56 | 70 |
| Media volume ($m^3$) | 15.9 | 19.2 |
| Bioretention media depth (cm) | 71.1 | 71.1 |
| Media composition | 93% sand, 7% fines | |
| Organic matter (by weight) and source | 5% pine bark mulch | |
| Gravel subbase thickness (cm) | 10 | |
| Average available ponding depth (cm) | 10 | |
| Estimated infiltration rate (cm $hr^{-1}$) | 0.08 | 0.10 |
| Drainage configuration | No underdrain | Underdrain |
| Underdrain diameter (cm) | - | 10 |
| Vegetation | Bald cypress tree (~5cm DBH) | |

# Construction and Installation

Study 3: Bioretention Suspended Pavement Systems

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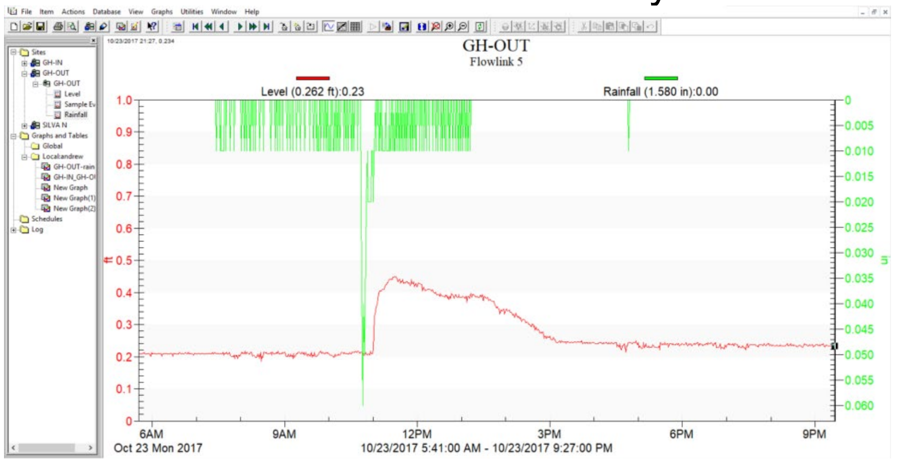
# Sample Collection and Data Analysis

- ISCO 6712 autosamplers installed at inlet/outlet of south site to collect flow-paced samples
  - Water quality samples collected within 24hr of a rainfall event
  - Composited samples analyzed for TSS, $NH_4^+$-N, $NO_x$-N, $PO_4^{3-}$, Cu, Pb, and Zn
- Hydrologic data analyzed using Flowlink v5.1, Hoboware, and Excel
  - Individual storms separated by minimum antecedent dry period of 6hr


Teledyne ISCO



# Hydrologic Monitoring Results

| | North Site | | South Site | |
|---|---|---|---|---|
| | (mm) | (%) | (mm) | (%) |
| **Inflow** | 1775 | - | 1887 | - |
| **Outflow** | - | - | 202 | 10.7 |
| **Overflow** | 3.3 | 0.2 | 11.4 | 0.6 |
| **Exfiltration/ET** | 1772 | 99.8 | 1673 | 88.7 |

- Total of 1922mm of rainfall recorded (median event of 8 mm) between April 2016 and July 2018
- 146 and 148 storm events collected for north and south sites
- Exfiltration from upper soil layers may have outweighed low infiltration rates of underlying soils
- 83% of storms completely captured by south site (123/148 storms); 79% at north site (116/146 storms)

# Pollutant Removal Performance

| Median pollutant conc. (st.dev.) for ten paired events | | | |
|---|---|---|---|
| **Pollutant** | Influent | Effluent | Significance |
| **TSS (mg $L^{-1}$)** | 167 (69) | 6 (21) | $p$<0.05 |
| **$NH_4^+$-N (mg $L^{-1}$)** | 0.01 (0.01) | 0.01* (0.00) | - |
| **$NO_x$-N (mg $L^{-1}$)** | 0.05 (0.13) | 0.11 (0.63) | - |
| **$PO_4^{3-}$ (mg $L^{-1}$)** | 0.06 (0.03) | 0.06* (0.00) | - |
| **Cu (µg $L^{-1}$)** | 0.5 (1.9) | 0.3 (0.08) | - |
| **Pb (µg $L^{-1}$)** | 1.6* (0.0) | 1.6* (0.0) | - |
| **Zn (µg $L^{-1}$)** | 7.9 (8.8) | 7.9 (18.2) | - |

Note: Asterisk (*) indicates that pollutant levels in all ten samples were below method detection limit.

# Conclusions

- Suspended pavement systems are effective at reducing runoff volumes
- Limited storage volume ("bowl volumes") in suspended pavement systems can lead to oversized practices
    - Sizing criteria may need to be revisited to account for small ponding volumes and the soil volumes required for tree growth
- Further research on pollutant removal performance needed – potentially linked to low influent concentrations and small sample size

# **Study 4:**
# Evaluating the Influence of Design Strategies and Meteorological Factors on Tree Transpiration in Bioretention Practices

Tirpak, R. A., J. M. Hathaway, and J. A. Franklin (2018). "Evaluating the Influence of Design Strategies and Meteorological Factors on Tree Transpiration in Bioretention Suspended Pavement Practices". Ecohydrology, e20373.

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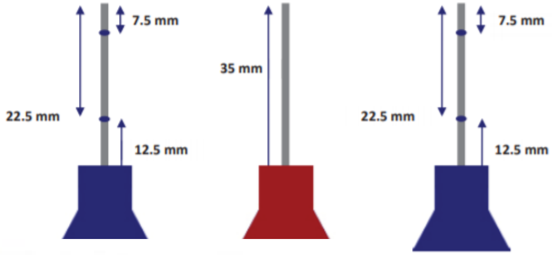
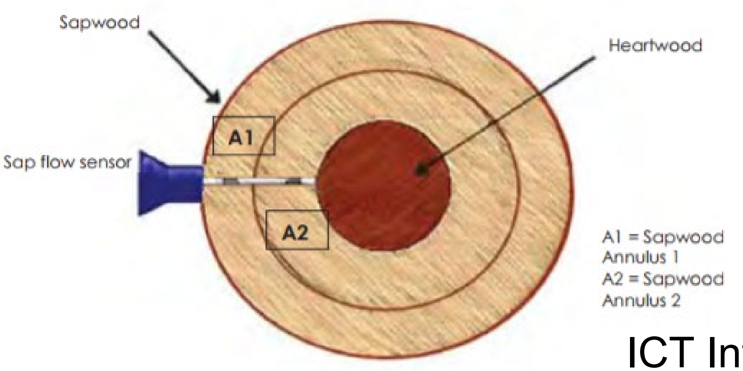
# Measuring Transpiration with Sap Flow Sensors

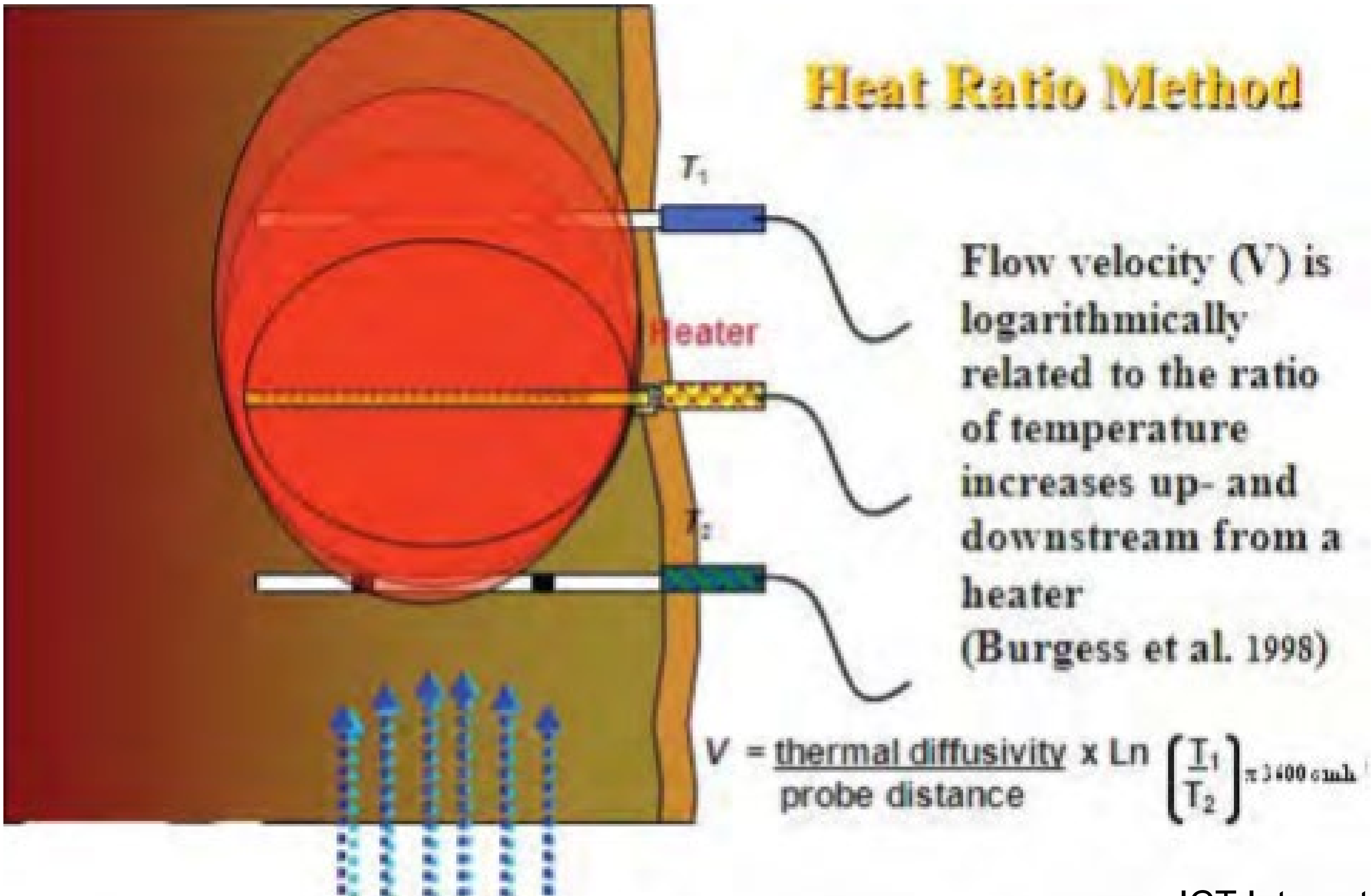
- ICT SFM1 sap flow sensors installed in bald cypress trees in spring 2017
- Readings conducted every 10min from May-July 2017
- Heat pulse velocity ($V_h$, cm hr$^{-1}$) used as a proxy for transpiration (Burgess, 2006)




ICT International

# Heat Ratio Method (HRM)

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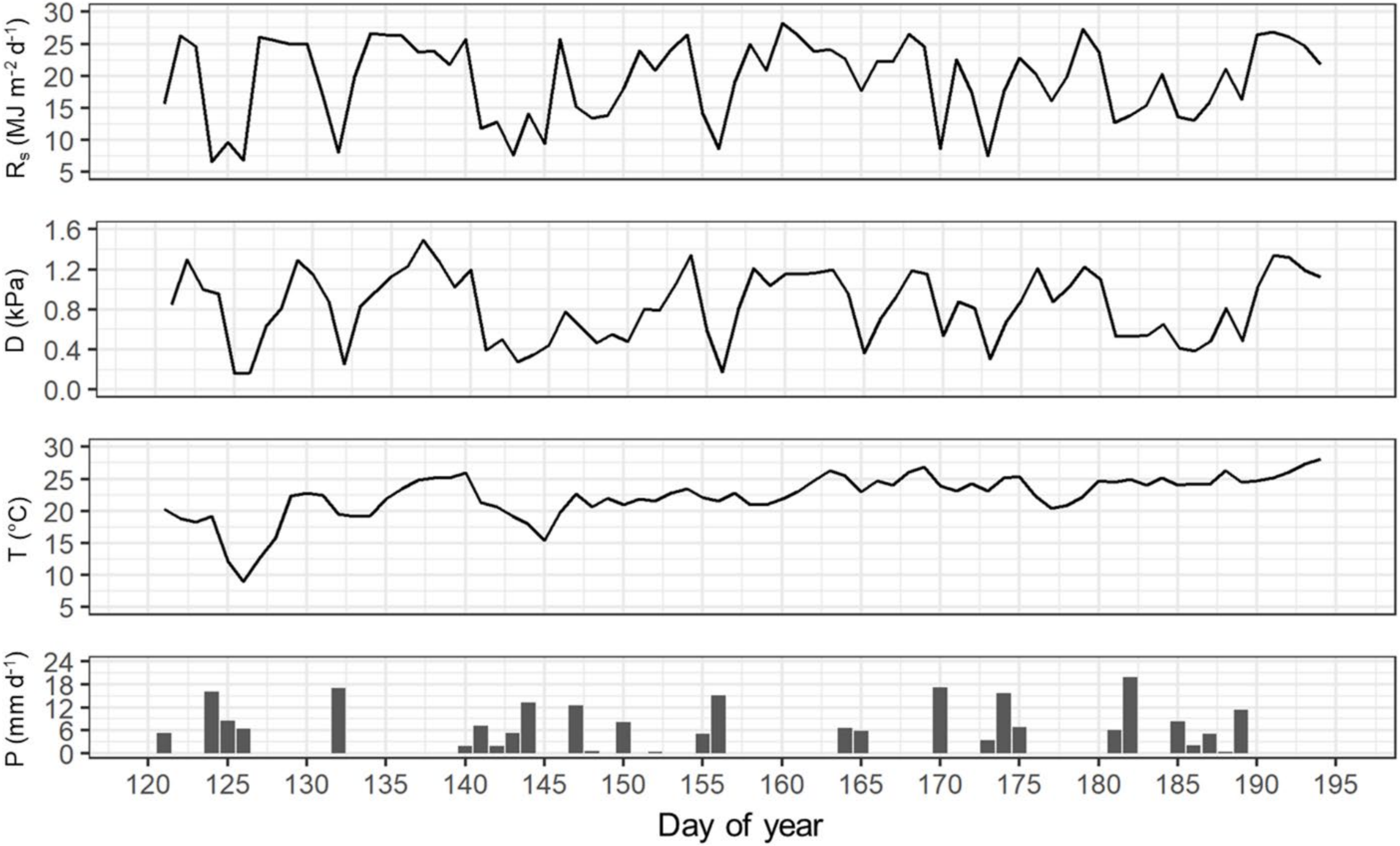
# Meteorological Data Collection

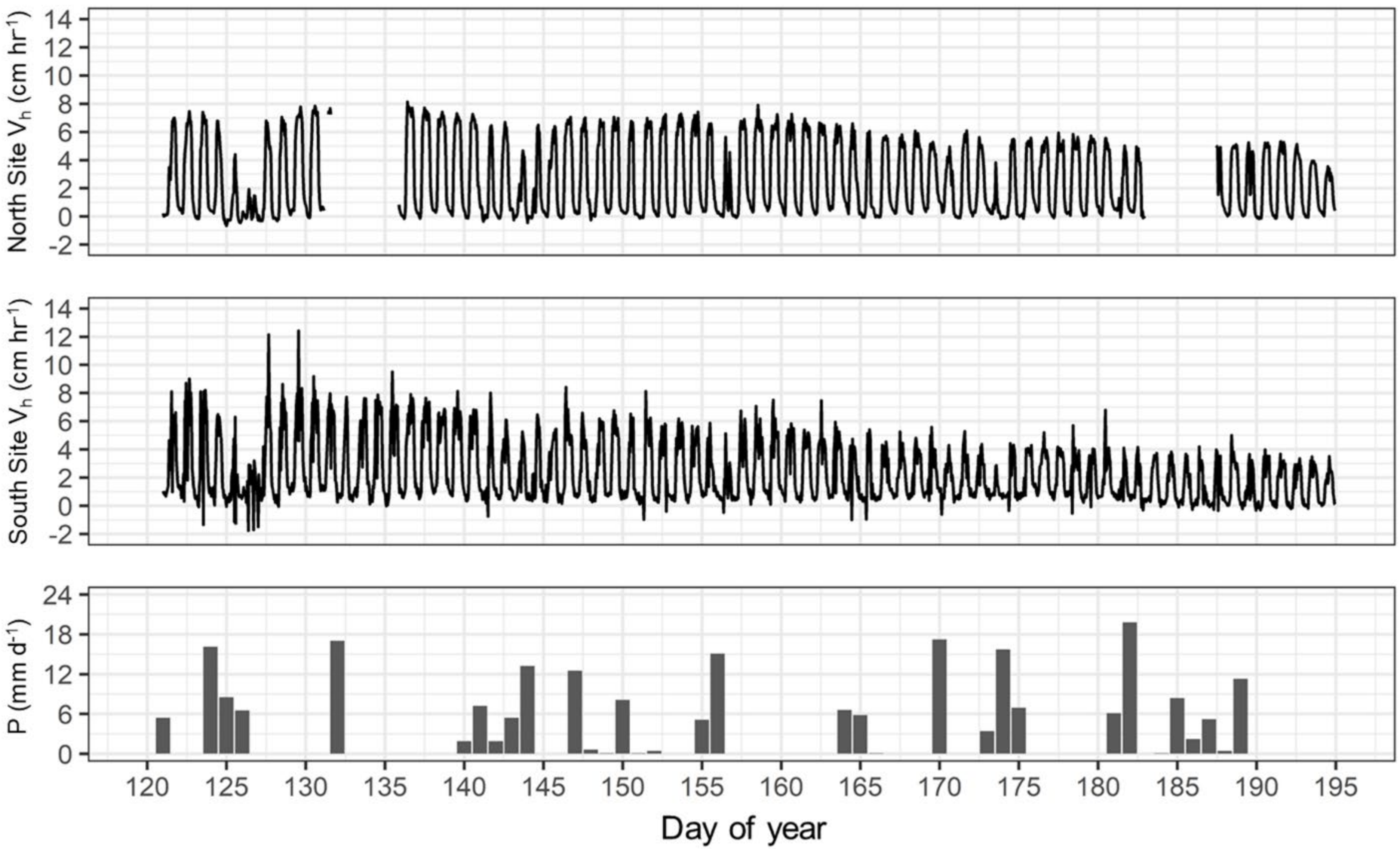
- Collected from UT Gardens weather station using Campbell Scientific loggers:
    - Temperature (T, °C)
    - Relative Humidity
    - Rainfall (P, mm)
    - Total Solar Radiation ($R_s$, MJ $m^{-2}$)
- Vapor Pressure Deficit (D, kPa) calculated using ASCE Penman-Monteith method (Allen et al., 2005)
- Onset UL-20 data loggers used to measure water level in wells

Campbell Scientific

# Meteorological Data



# Heat Pulse Velocity (Transpiration)



# Summary of Meteorological and Transpiration Data

| | |
|---|---|
| Duration of Study (rain days) | 74 (33) |
| Mean High/Low Temperatures (°C) | 28 / 9 |
| Mean Daily Temperature (°C) | 22.3 |
| Mean Daily Vapor Pressure Deficit (kPa) | 0.83 |
| Daily Total Solar Radiation (MJ $m^{-2}$) (min-max) | 6.7 - 28.2 |
| Mean Water Level in Well - North (cm) | 15.5* |
| Mean Water Level in Well - South (cm) | 8.2* |
| Mean Heat Pulse Velocity - North (cm $hr^{-1}$) | 2.65* |
| Mean Heat Pulse Velocity – South (cm $hr^{-1}$) | 2.38* |

Note: Asterisk (*) indicates significant differences between north and south sites ($p$<0.0001).

# Regression Modeling Results

| Model Parameter | North Site | South Site |
|---|---|---|
| D, kPa | 1.80 | 1.35 |
| Lag D, kPa | -1.60 | -1.06 |
| Lag T, °C | - | -0.05 |
| Lag $V_h$, cm $hr^{-1}$ | 0.80 | 0.77 |
| Intercept | - | 1.14 |
| Final Model | $V_h$ = 1.80*D – 1.60*lag(D) + 0.80*lag($V_h$) | $V_h$ = 1.35*D – 1.06*lag(D) – 0.05*lag(T) + 0.80*lag($V_h$) + 1.14 |
| $R^2$ | 0.79 | 0.80 |

- Atmospheric moisture conditions had greater influence on north site sap flow compared to south site
  - Changes in D, lag(D) produced **33%** and **51%** larger responses in north site than south site, respectively
- Stomatal regulation to limit water losses occurring at south site (lower water availability); less necessary at north site

# Conclusions and Recommendations

- Transpiration rates and water availability were significantly different between the two suspended pavement systems
  - Lower transpiration rates were observed in more water-limiting conditions
- Atmospheric moisture significantly influenced transpiration rates, though site water availability mitigated the response of transpiration to vapor pressure deficit
- Higher transpiration rates achieved when increased (though not saturated) soil moisture conditions in upper layers are promoted in design

# Overall Conclusions

- Tree health in bioretention is improved when species-specific growing preferences resemble the bioretention environment; health is influenced by media composition, chemistry, and species selection/planting location

- Trees provide significant contributions to bioretention hydrology via ET and differences between species exist

# Overall Conclusions cont'd.

- Suspended pavement systems used in stormwater management applications are effective at mitigating runoff volumes; more research is needed to better characterize their pollutant removal capabilities

- Tree transpiration rates are influenced by site and atmospheric conditions; design strategies that promote higher water availability can influence the role of transpiration in bioretention hydrology

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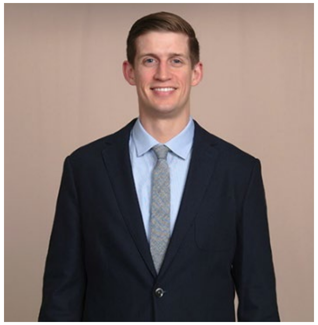


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