Water relations of trees growing in Green Infrastructure (GI) storm water trenches

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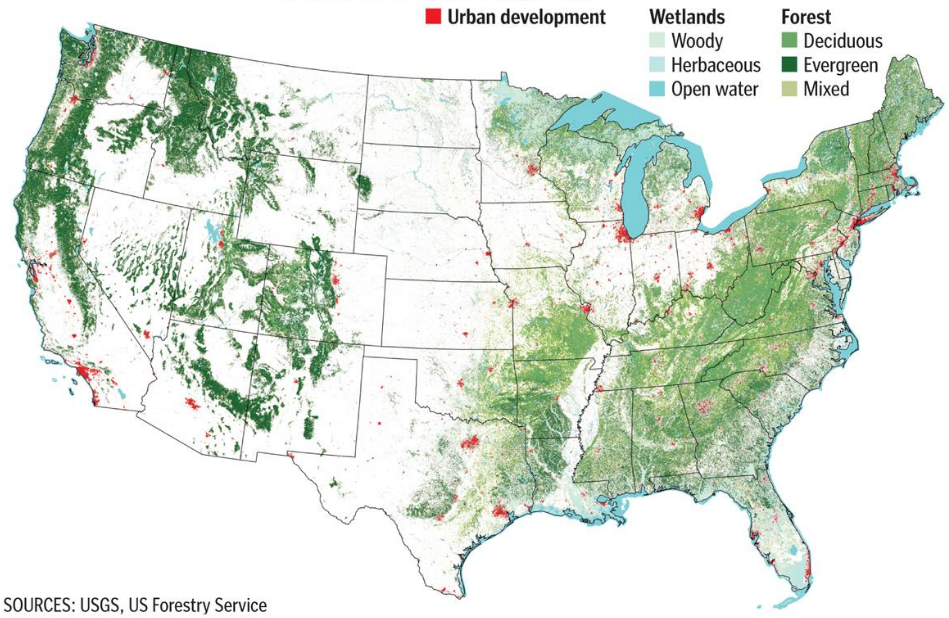
OLD-GROWTH FOREST

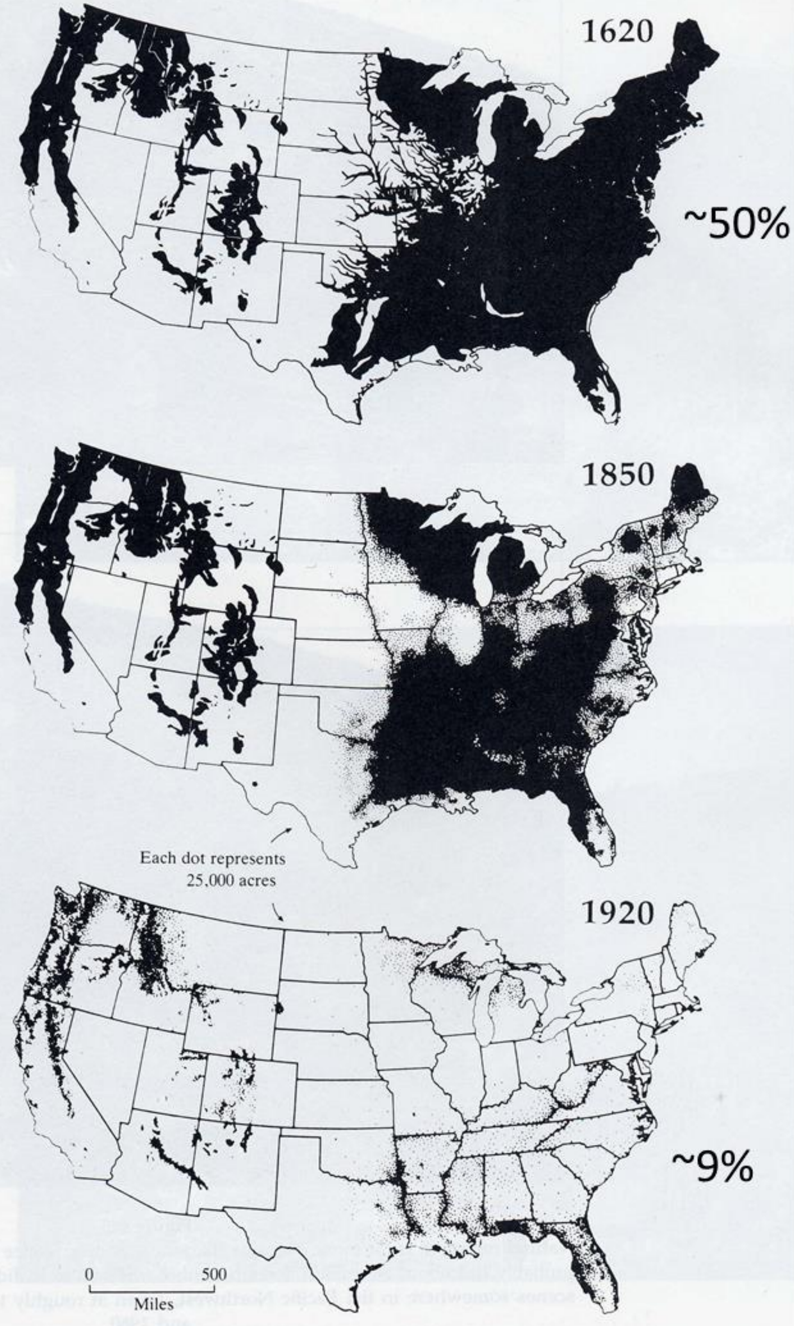
Most of the original trees had been cut down by the beginning of the 20th century.

FORESTED LAND, 2006

Forests have since reclaimed abandoned farms and filled in around suburban development.



SOURCES: USGS, US Forestry Service



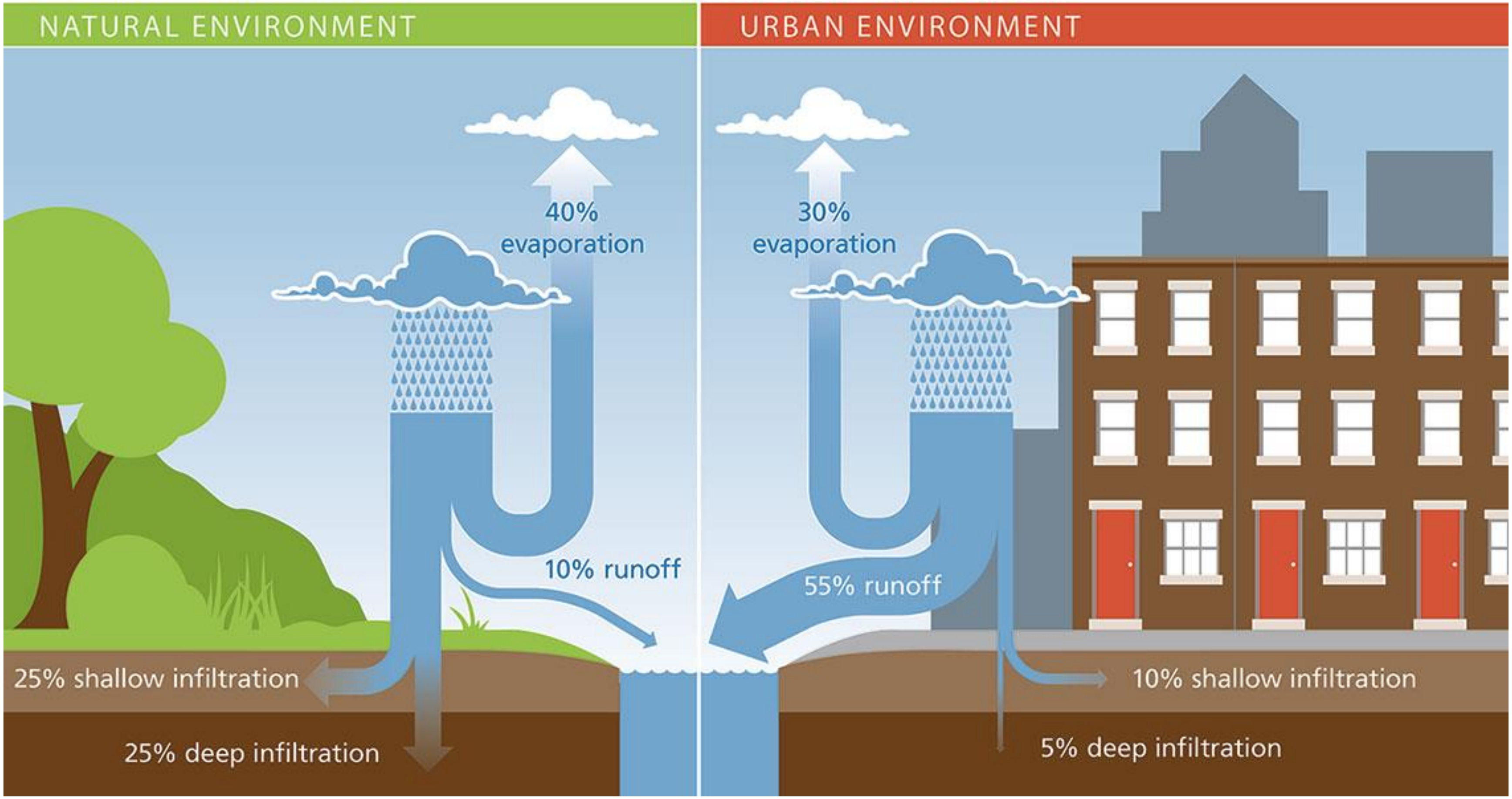

A SURVEY of the CITY of PHILADELPHIA and its Environs shewing the several Works constructed by his MAJESTY's Troops, under the Command of Sir WILLIAM HOWE, since their possession of that City 26th September 1777, comprehending likewise the Attacks against Fort Mifflin on Mud Island, and until it's Reduction.
16th November 1777.
Chief Engineer
To the Honble Sir WILLIAM HOWE, K.B. GENERAL and COMMANDER IN CHIEF of all His MAJESTY's Forces, within the Colonies laying on the ATLANTIC Ocean, from NOVA-SCOTIA to WEST FLORIDA, inclusive &c. &c. &c.
PROVINCE OF PENNSYLVANIA
PHILADELPHIA
PASSYUNK TOWNSHIP
MOYAMENSING TOWNSHIP
RIVER OF SCHUYLKILL
RIVER OF DELAWARE
Wind Mill Island
Hollanders Creek
Gloucester Point
Glovester
Newton Creek
Mingo Creek
Province Island
League Island
Part of Carpenters Island
Little Mud Island

A conjectural sketch of the whole city of Philadelphia about the year 1707. Dock Creek may plainly be seen, with its pond at Fourth and High Streets, and its dock and mouth in the left foreground; also the high river banks in which the first settlers dug their caves. About the left half of this picture shows what developed into the Independence Square Neighborhood. From a print at the Historical Society of Pennsylvania.

An 1840 bird's eye view of the Delaware River and Philadelphia, looking downstream from present-day Center City. Market Street is the large street

Impervious surface!

The fate of precipitation

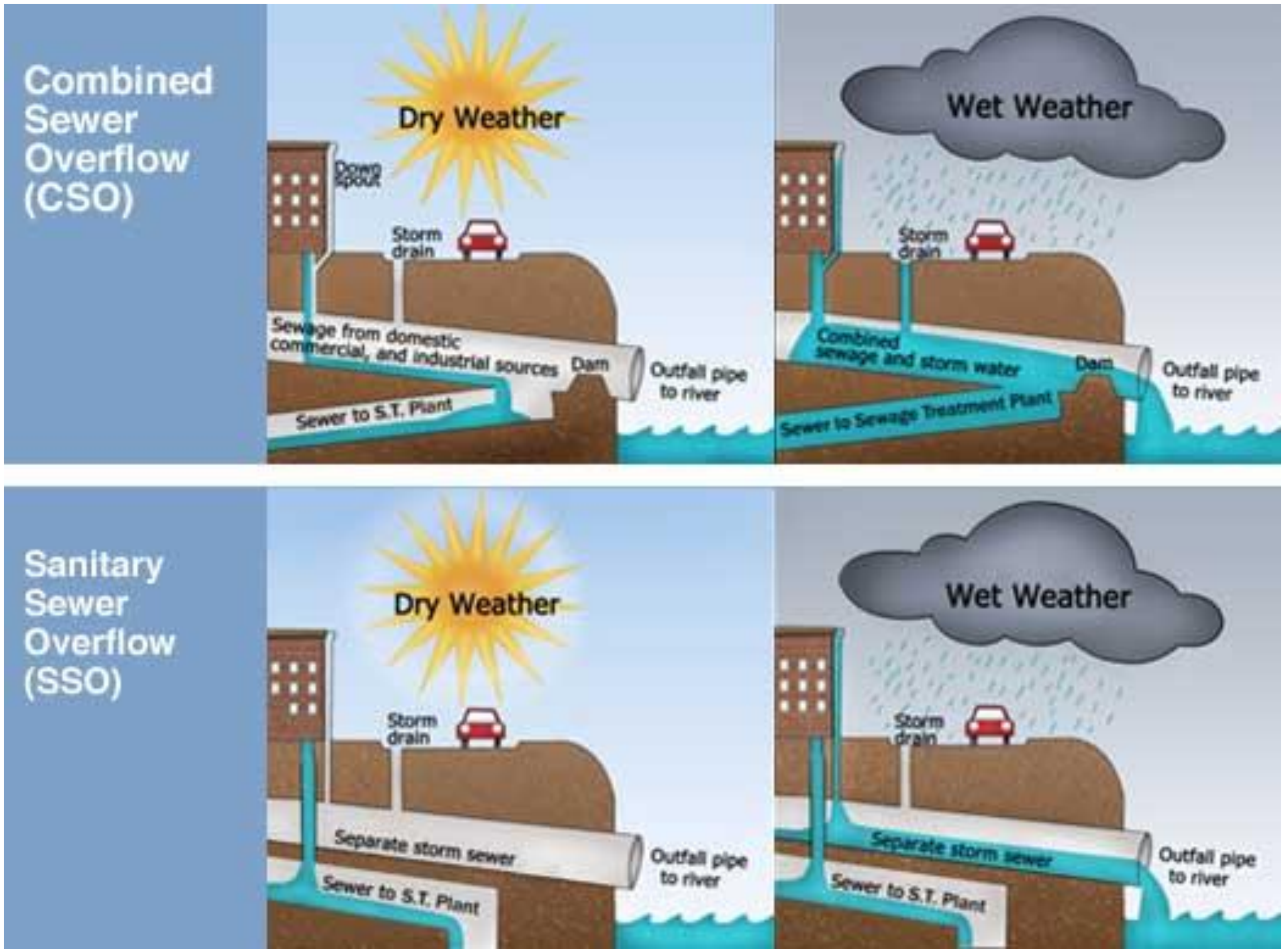


http://www.phila.gov/water/PublishingImages/naturalvsurbanrunoff.jpg

TYPES OF SEWERS IN PHILADELPHIA

60%

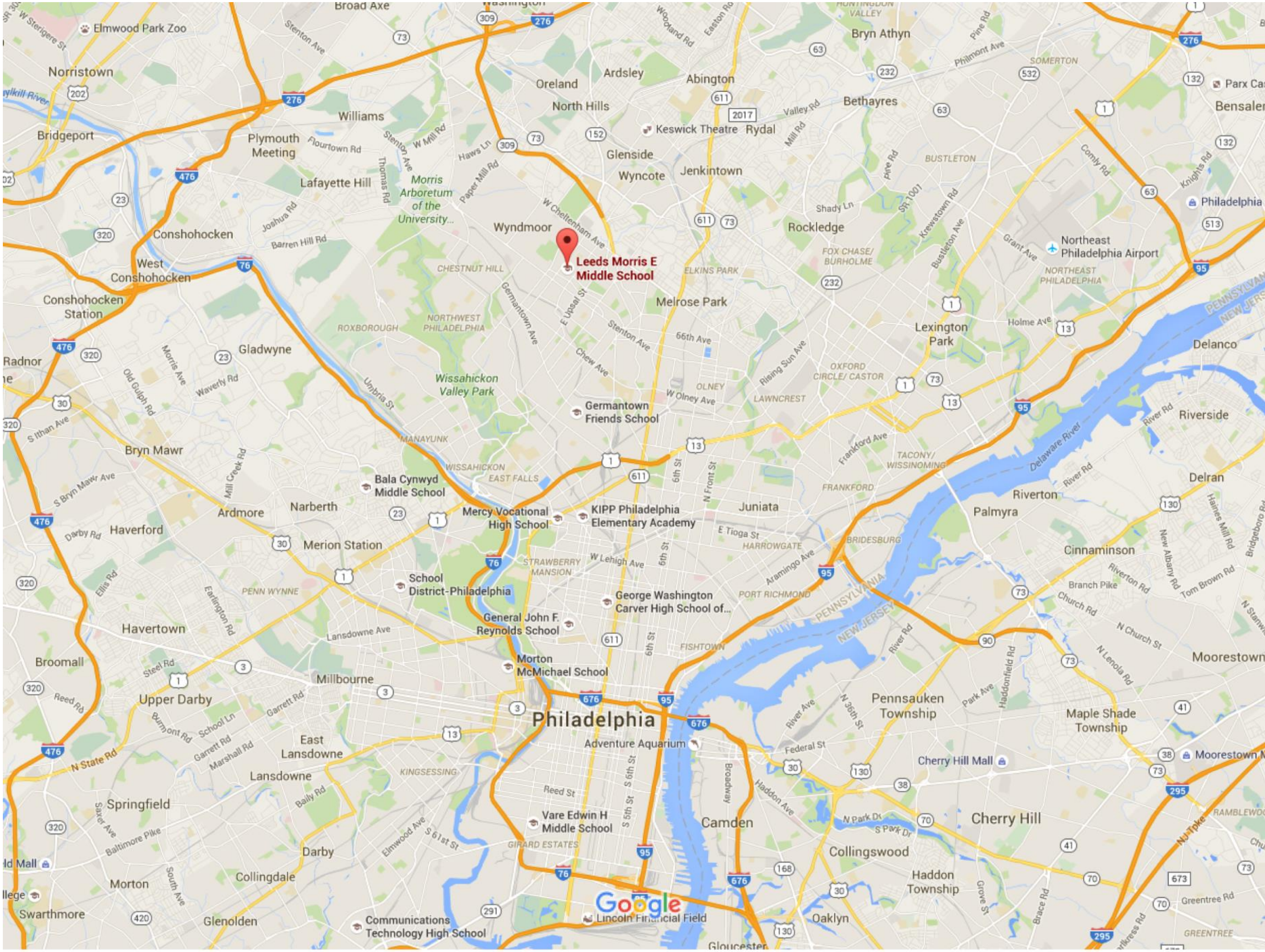
40%



http://www.beachapedia.org/File:Cso-ss0-524.jpg

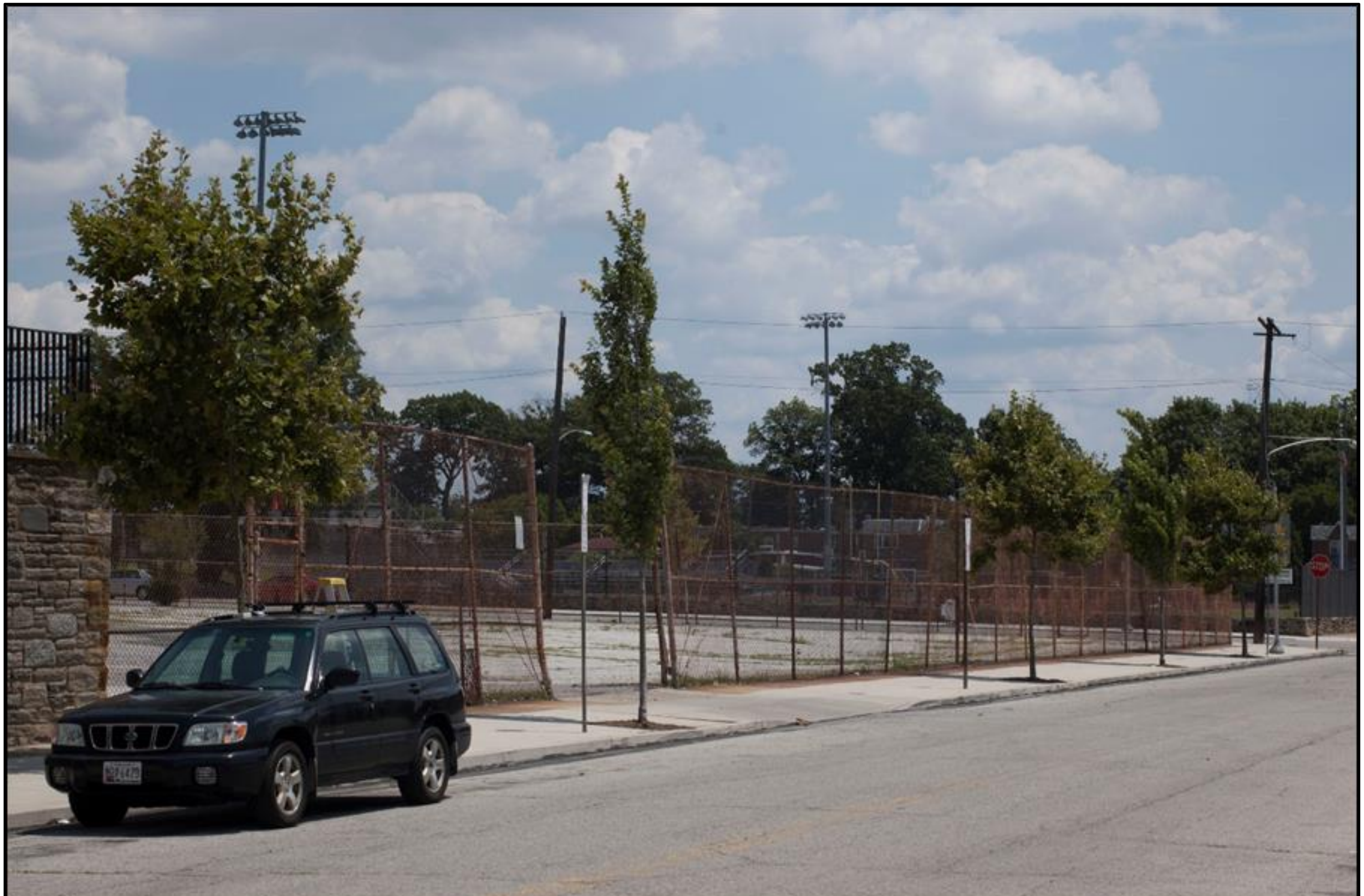
- Serving more than three-quarters of the city's residents, the combined sewer system is in the oldest and densest parts of the city,
  - Center City, South Philadelphia, West Philadelphia, North Philadelphia, Bridesburg/Kensington/Richmond, East Mt. Airy and East Germantown, parts of near Northeast
- 164 combined sewer outfalls (CSOs) along the Delaware and Schuylkill rivers and the Cobbs, Tookany/Tacony-Frankford, and lower Pennypack creeks.

http://www.phillywatersheds.org/watershed_issues/stormwater_management/combined_sewer_system


Leeds Morris E
Middle School
Elmwood Park Zoo
Norristown
Bridgeport
Williams
Plymouth
Meeting
Lafayette Hill
Morris
Arboretum
of the
University...
Oreland
Ardsley
Abington
North Hills
Keswick Theatre
Rydal
Glenside
Wyncote
Jenkintown
Bryn Athyn
Bethayres
Bensalem
Parx Casir
Philadelphia Mi
Northeast
Philadelphia Airport
Rockledge
Wyndmoor
Conshohocken
West
Conshohocken
Conshohocken
Station
CHESTNUT HILL
ELKINS PARK
Melrose Park
Lexington
Park
Delanco
Gladwyne
Radnor
ROXBOROUGH
NORTHWEST
PHILADELPHIA
Wissahickon
Valley Park
Germantown
Friends School
OLNEY
LAWNCREST
OXFORD
CIRCLE/ CASTOR
Riverside
Bryn Mawr
MANAYUNK
WISSAHICKON
EAST FALLS
Bala Cynwyd
Middle School
TACONY/
WISSINOMING
FRANKFORD
Delran
Riverton
Palmyra
Ardmore
Narberth
Haverford
Merion Station
Mercy Vocational
High School
KIPP Philadelphia
Elementary Academy
Juniata
BRIDESBURG
HARROWGATE
Cinnaminson
STRAWBERRY
MANSION
School
District-Philadelphia
PENN WYNNE
George Washington
Carver High School of...
PORT RICHMOND
Havertown
General John F.
Reynolds School
FISHTOWN
Broomall
Morton
McMichael School
Millbourne
Moorestown
Upper Darby
Philadelphia
Pennsauken
Township
Maple Shade
Township
East
Lansdowne
Adventure Aquarium
Cherry Hill Mall
Moorestown Ma
Lansdowne
KINGSESSING
Springfield
Camden
Cherry Hill
Vare Edwin H
Middle School
RAMBLEWOOD
Darby
GIRARD ESTATES
Collingswood
Collingdale
Haddon
Township
Morton
Swarthmore
Glenolden
Communications
Technology High School
Lincoln Financial Field
Oaklyn
Gloucester
GREENTREE
Google


Woolston Ave
E Gorgas Ln
Lowber Ave
E Sedgwick St
experiment 1
E Mt Pleasant Ave
Rodney St
© 2016 Google
Google earth
1992
Imagery Date: 10/7/2011 lat 40.070241° lon -75.174458° elev 339 ft eye alt 1650 ft

- Tree pit with stormwater trench

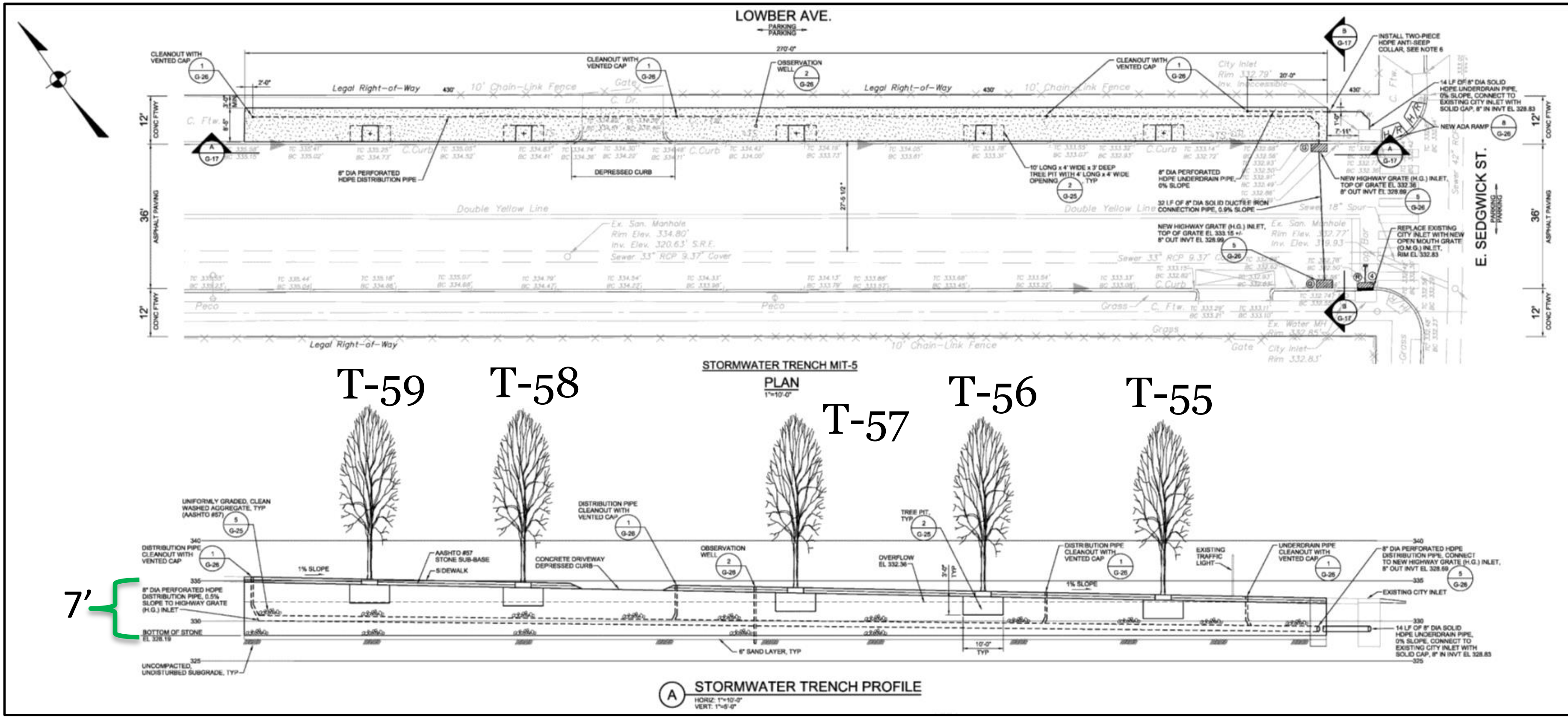


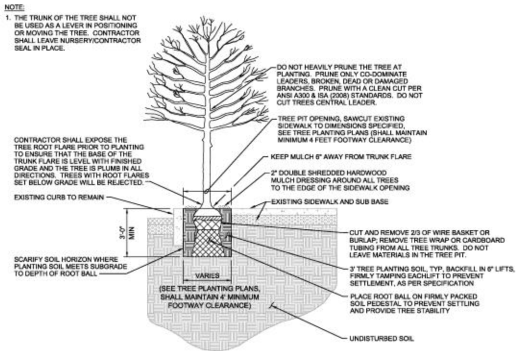
T-55, T-57, T-59:

Platanus x *acerifolia* 'Bloodgood' (London plane)

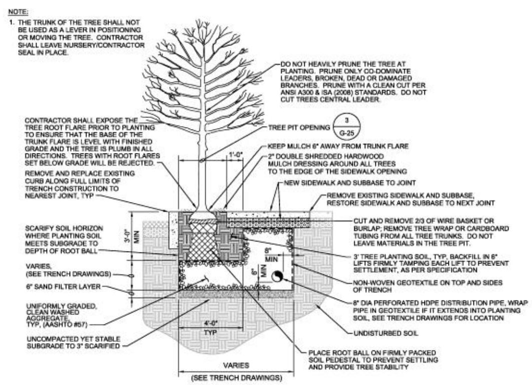
T-56, T-58:

Acer rubrum 'Armstrong' (red maple)

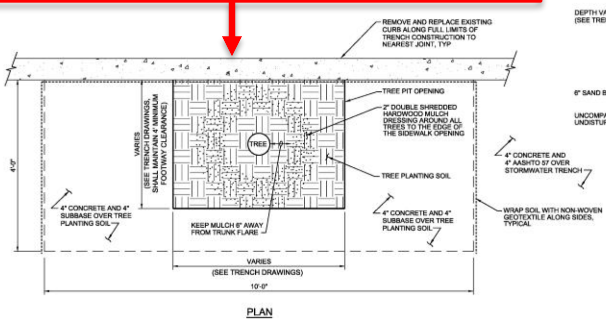




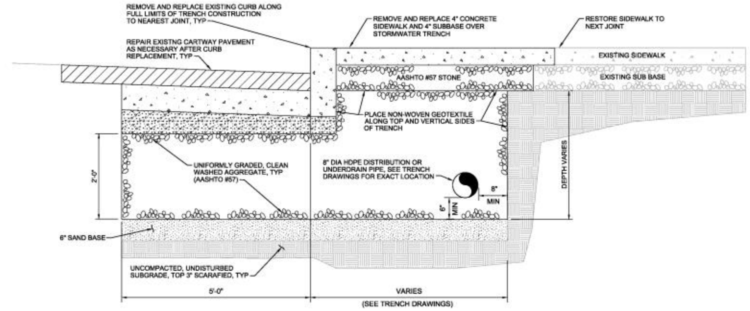
1 TREE PIT DETAIL NOT IN STORMWATER TRENCH
NTS



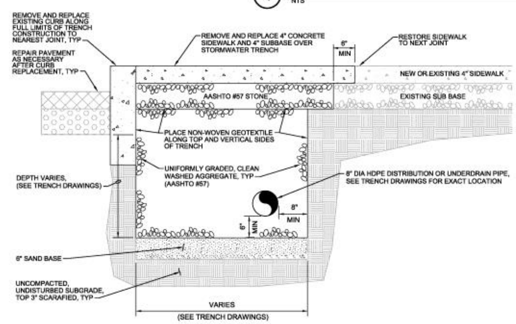
2 TYPICAL TREE PIT DETAIL WITHIN STORMWATER TRENCH
NTS



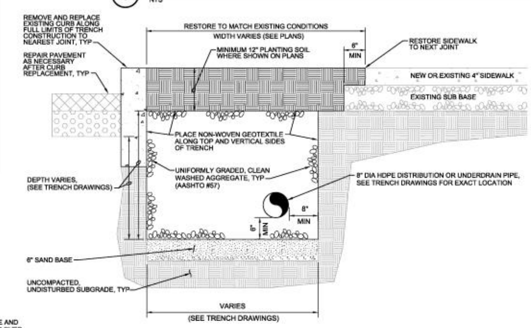
3 TYPICAL TREE PIT PLAN WITHIN STORMWATER TRENCH
NTS



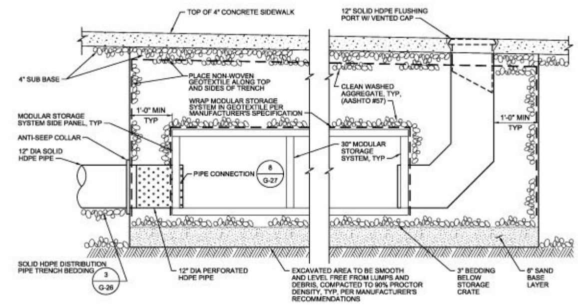
4 TYPICAL STORMWATER TRENCH UNDER SIDEWALK AND STREET
NTS



5 TYPICAL STORMWATER TRENCH UNDER SIDEWALK
NTS



6 TYPICAL STORMWATER TRENCH UNDER GRASS
NTS



NOTES:

1. PROVIDE A MINIMUM 2'-0" COVER OVER MODULAR STORAGE SYSTEM (INCLUDING 4" CONCRETE SIDEWALK).
2. RESTORE SURFACE TO MATCH EXISTING CONDITIONS AND EXISTING SLOPES. INSTALL 12 INCHES OF PLANTING SOIL IN GRASS AREAS AND SEED.
3. AGGREGATE FOR STORMWATER TRENCHES SHALL BE CLEAN-WASHED PRIOR TO PLACEMENT.
4. INSTALL INLET FILTER INSERTS IN ALL GREEN INLETS DRAINING INTO STORMWATER TRENCHES VIA DISTRIBUTION PIPING (6 G-27)
5. INSTALL TWO-PIECE HDPE ANTI-SEEP COLLAR PER PWD SPECIFICATION. INSTALL COLLAR FLUSH TO EDGE OF TRENCH.
6. SIDEWALK TO BE REPLACED IN FULL WIDTH TO CLOSEST JOINT FROM DISTURBED AREA.
7. CURBING TO BE REPLACED TO NEAREST JOINT FROM DISTURBED AREA.
8. ALL INVERT ELEVATIONS TO BE FIELD VERIFIED BY CONTRACTOR.

7 TYPICAL MODULAR STORAGE SYSTEM DETAIL
NTS

GREEN STREETS CONSTRUCTION PROJECT

CONSTRUCTION DETAILS #1

BASE PLAN PREPARED BY:	PREPARED FOR CITY OF PHILADELPHIA BY:	APPROVED ____ CH2M HILL	CITY OF PHILADELPHIA WATER DEPARTMENT
HUNT ENGINEERING COMPANY 22 EAST KING STREET MALVERN, PA 19355 (P)610-644-4600 (F)610-644-2466 WWW.HUNTENGINEERING.COM	CH2MHILL. 1717 ARCH STREET SUITE 4400 PHILADELPHIA, PA 19103 (P)215-563-4220 WWW.CH2MHILL.COM	WORK NO. S-50029-G SHEET NO. G-25 OF 28 SHEETS	DRAWN BY: M.REICHERT PROJECT ENGR.: L.THARPS SUPERVISOR: B.MARENGO DATE: FEB 2012

water relations of trees in GI tree trench systems

- Experiment 1: 5 trees/ 2 species in a single GI tree trench
  - Stomatal conductance
  - Leaf water potential
  - LAI
- Experiment 2: 25 trees of 13 different species/cultivars in multiple GI tree trenches and tree pits
  - Stomatal conductance

Experiment 1:

Water relations of *Acer rubra* 'Armstrong' and *Platanus × acerifolia* 'Bloodgood' trees in a GI tree trench system

1. Assess the rate of water movement out of tree trench systems via stomatal conductance
2. Evaluate plant moisture stress of different tree species

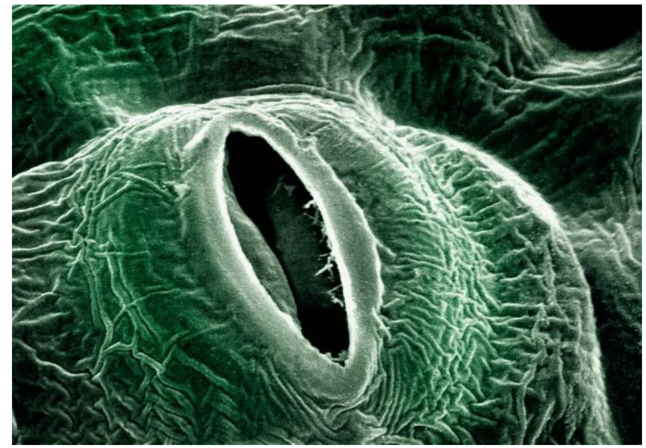
Stomatal conductance - g_s

leaf porometer model SC-1 (Decagon Devices, Pullman, WA).

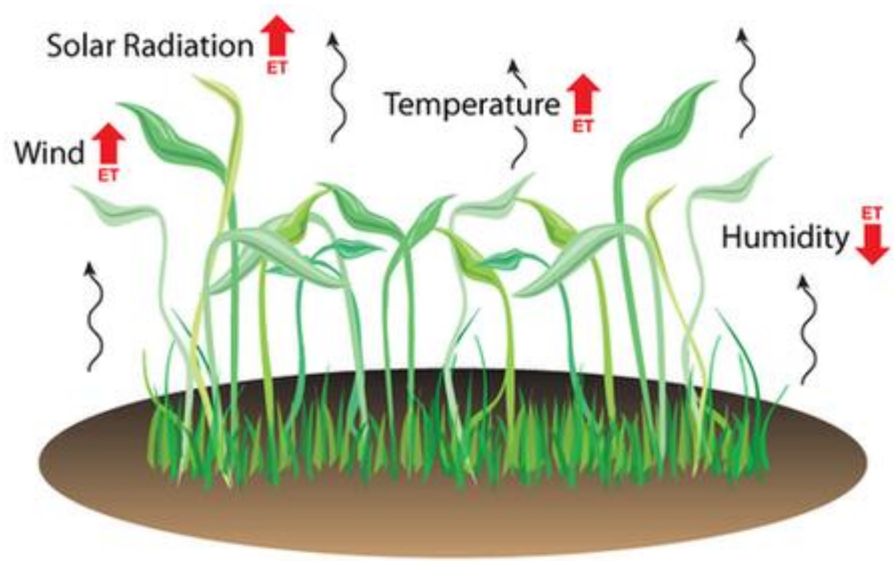
Stomatal conductance - g_s

- g_s is a function of:

  Plant and stomatal characteristics (density, size, and degree of opening)

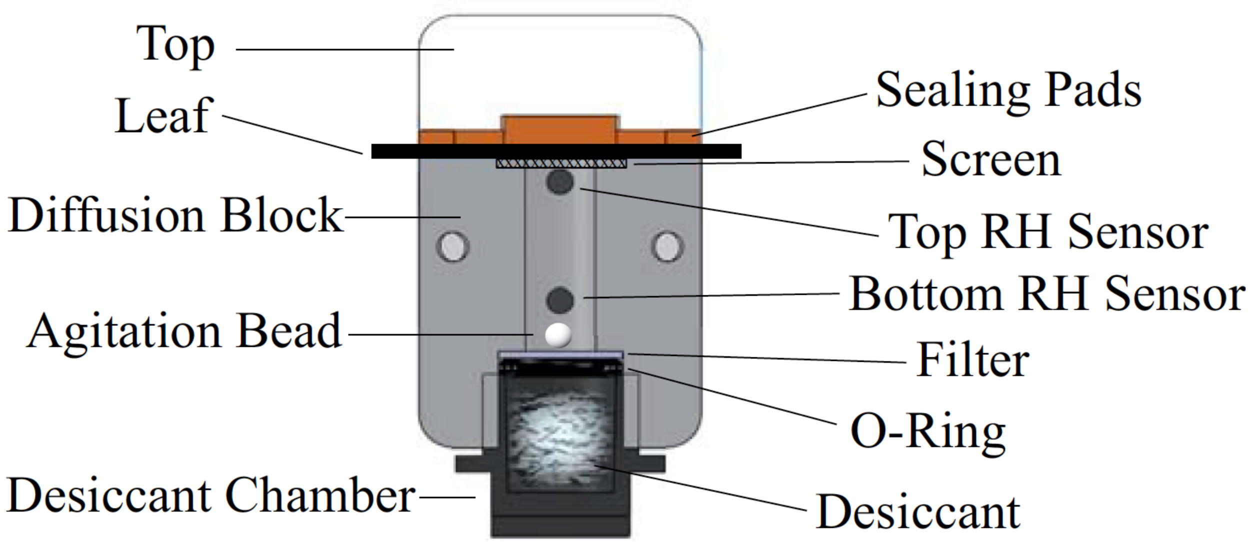


  Environmental factors (solar radiation, wind speed/humidity/boundary layer, precipitation/water availability)



Steady-state porometer

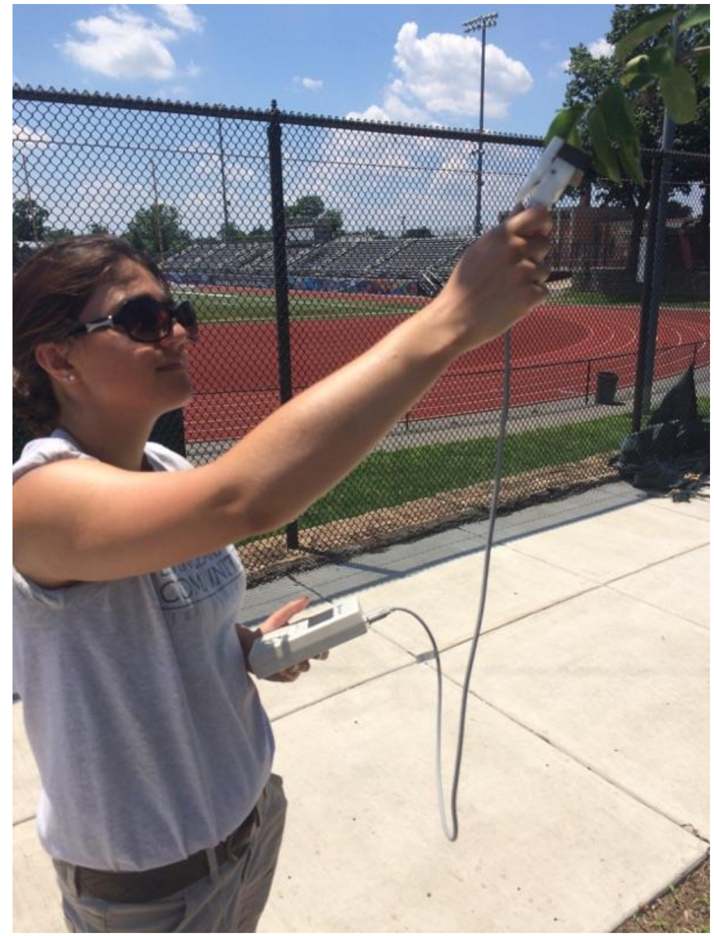
The leaf porometer measures stomatal conductance by putting the conductance of a leaf in series with two known conductance elements, and comparing the humidity measurements between them.



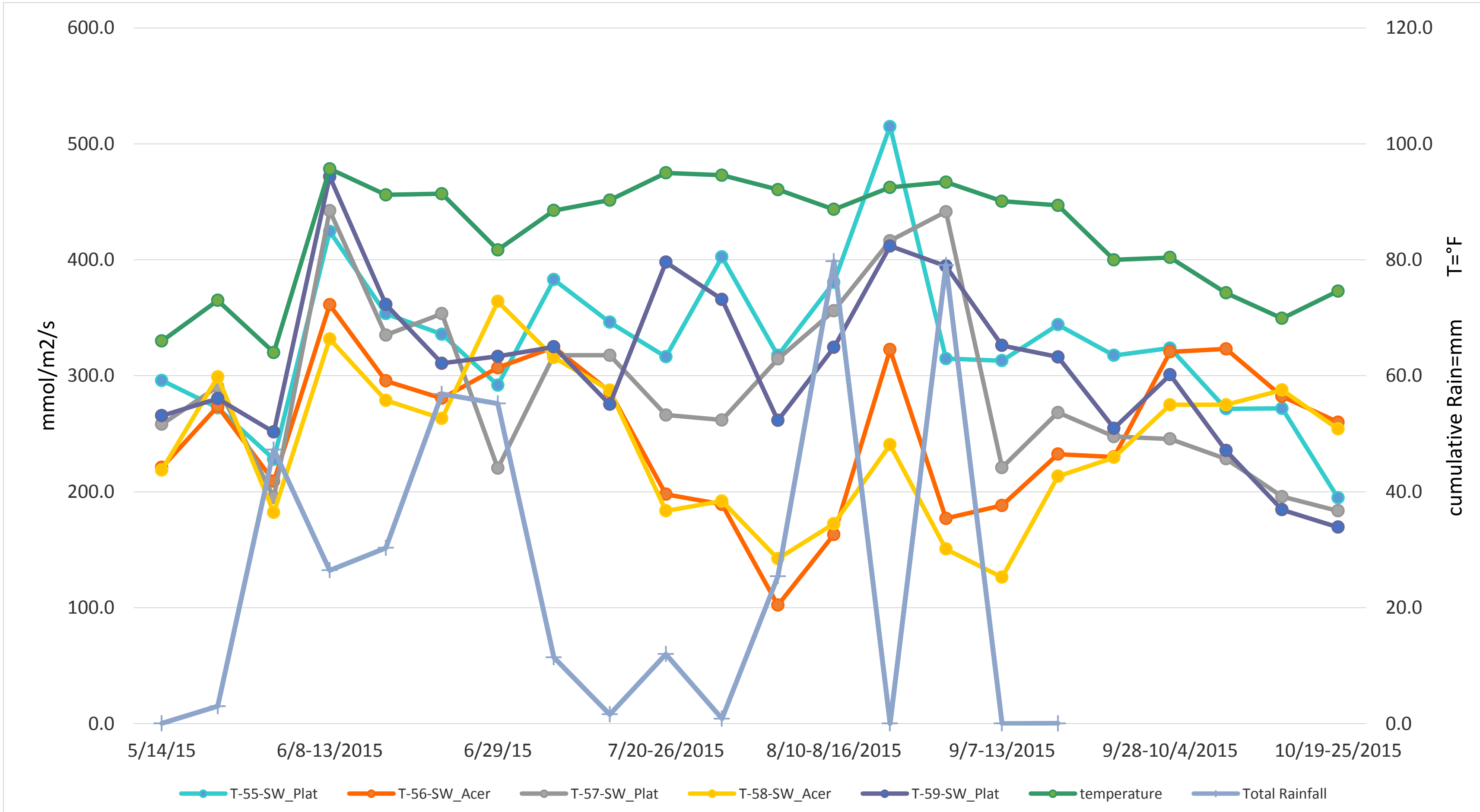
Measures mmol/m^2s (millimoles per meter squared per second)

Measurements of g_s

- From late May to early November ~daily measurements
- Taken during the period of peak irradiance, from 11:45 a.m. to 2:45 p.m.
- Three different leaves that were fully exposed to direct sunlight were sampled



Weekly stomatal conductance rates for *Acer rubra* 'Armstrong' and *Platanus* x *acerifolia* 'Bloodgood'

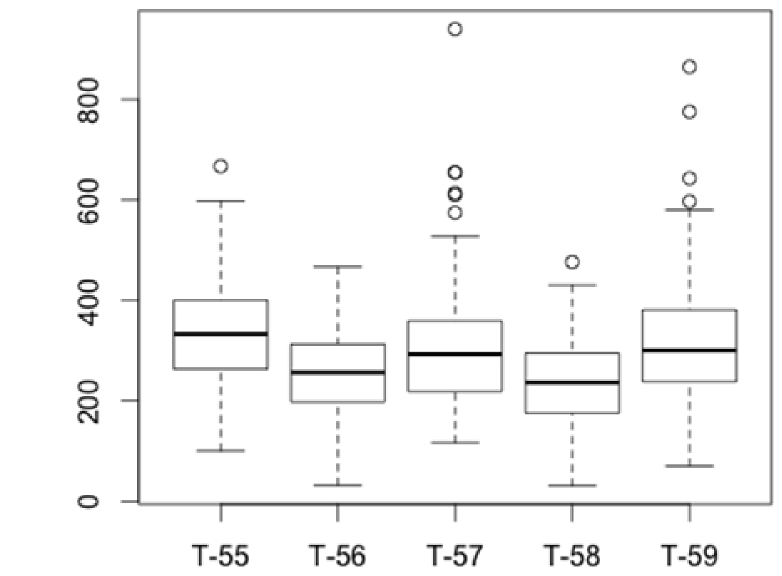


Average conductance dropped during mid- summer months for *A. rubrum* while *P.* × *acerifolia* showed more stability.

Total average stomatal conductance

A Kruskal-Wallis test (one-way ANOVA on ranks) was performed followed by a post hoc Dunn test. The test shows a significant difference between species but not within species with the exception of T-55.

T-55, a *P.* x *acerifolia,* shows significant difference from all other trees



Sample	T-55	T-56	T-57	T-58
T-56	7.538204 0.0000*			
T-57	3.649419 0.0002*	-3.879578 0.0001*		
T-58	9.105290 0.0000*	1.595306 0.0615	5.458362 0.0000*	
T-59	2.492492 0.0079*	-5.022251 0.0000*	-1.148662 0.1253	6.593815 0.0000*

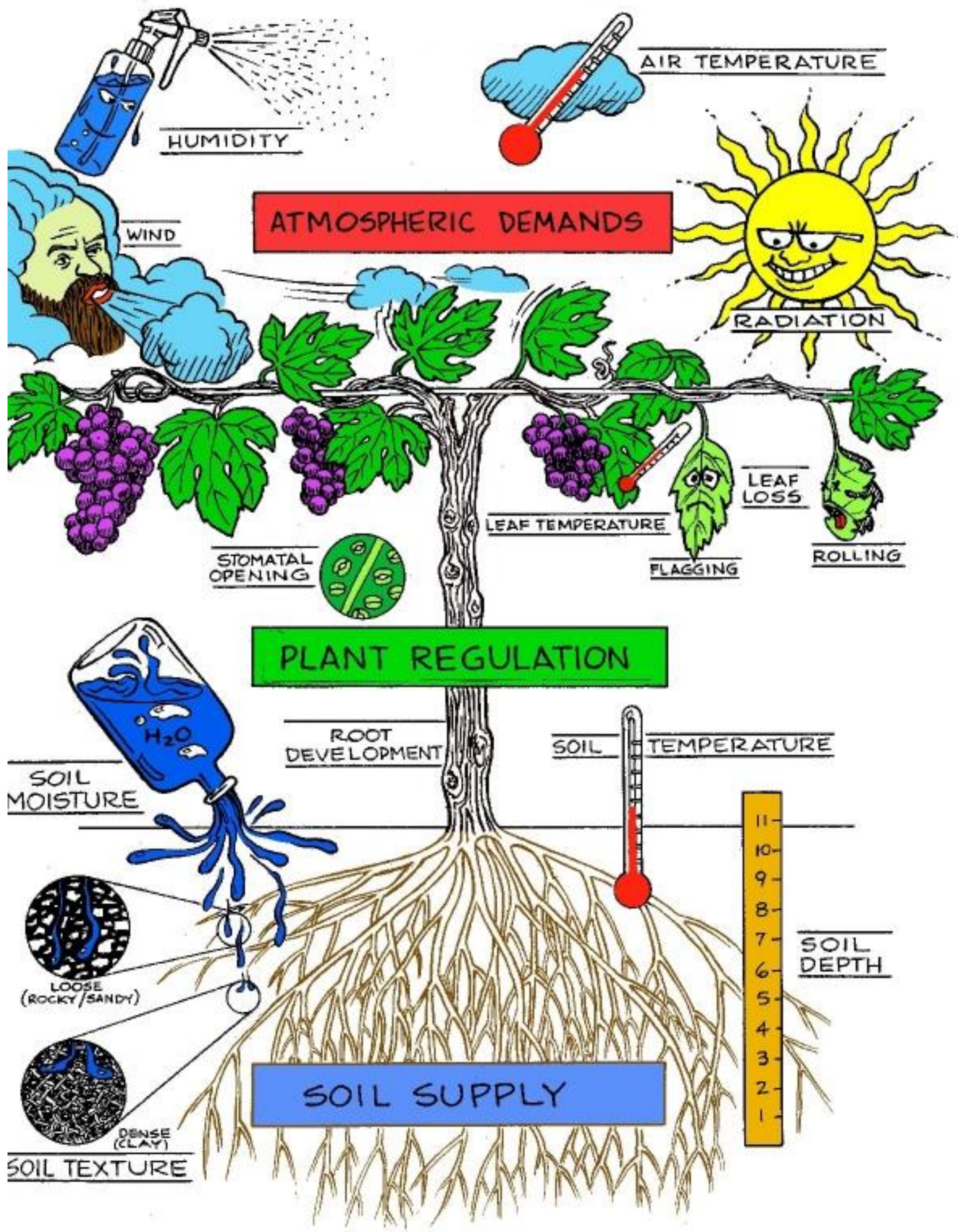
Results of Dunn's Test (Benjamini-Hochberg method) *Indicates significant difference among samples. Upper number signifies Dunn's pairwise z test statistic

Leaf water potential $(\Psi)_{lf}$

- Model 615 Pressure Chamber Instrument
  Pressure chamber or "pressure bomb"

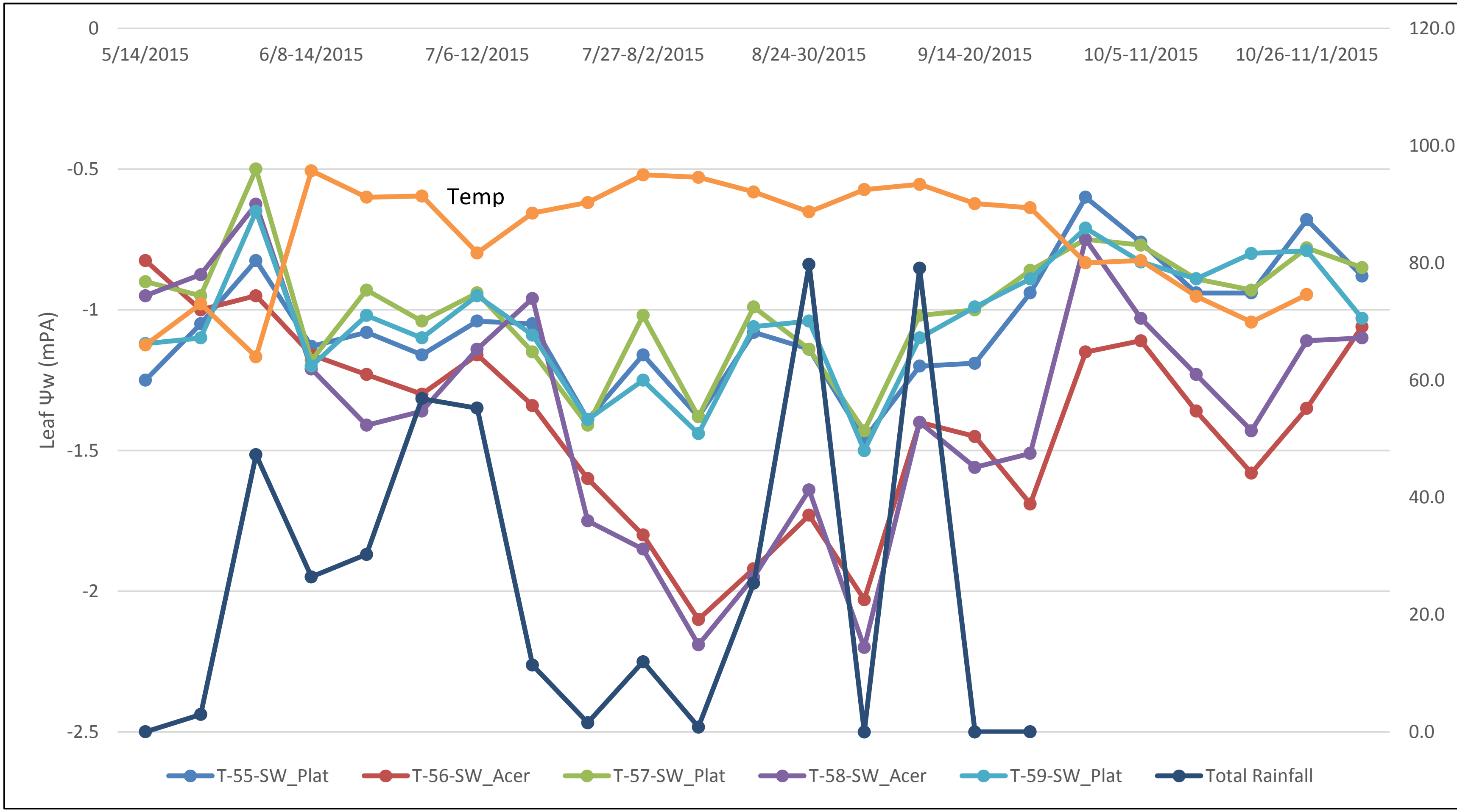
  (PMS Instrument Company, Albany, OR)

- Plant moisture stress (PMS), or plant water potential, indicates the demand for water within a plant
- A low pressure (e.g. 3 bar or 45 psi) is sufficient to force water to the cut surface of the sample, the plant is under relatively low moisture stress (high water potential) and probably has sufficient water for its growth process
- If 20 bar pressure is required to force water to the cut surface, the moisture stress is relatively high (low water potential).



http://www.pmsinstrument.com/resources/pms-meaning-and-importance

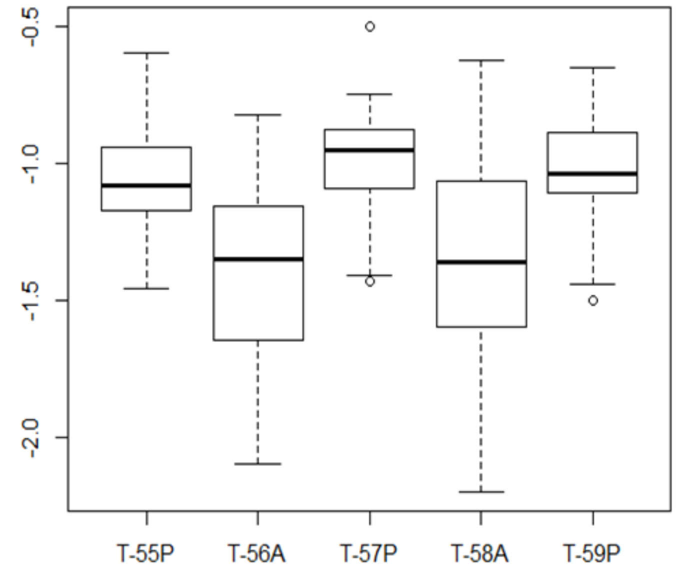
Weekly leaf water potential readings for *Acer rubra* 'Armstrong' and *Platanus* x *acerifolia* 'Bloodgood'



Weekly water potential readings dropped drastically during mid- summer months for *A. rubrum* while *P.* x *acerifolia* showed more stability during those months, despite having lower readings as well.

A kruskal-Wallis test showed significant difference between ranked data (P = 1.777e-05)

The post-hoc Dunn's test showed a significant difference in leaf water potential between species but not within species.

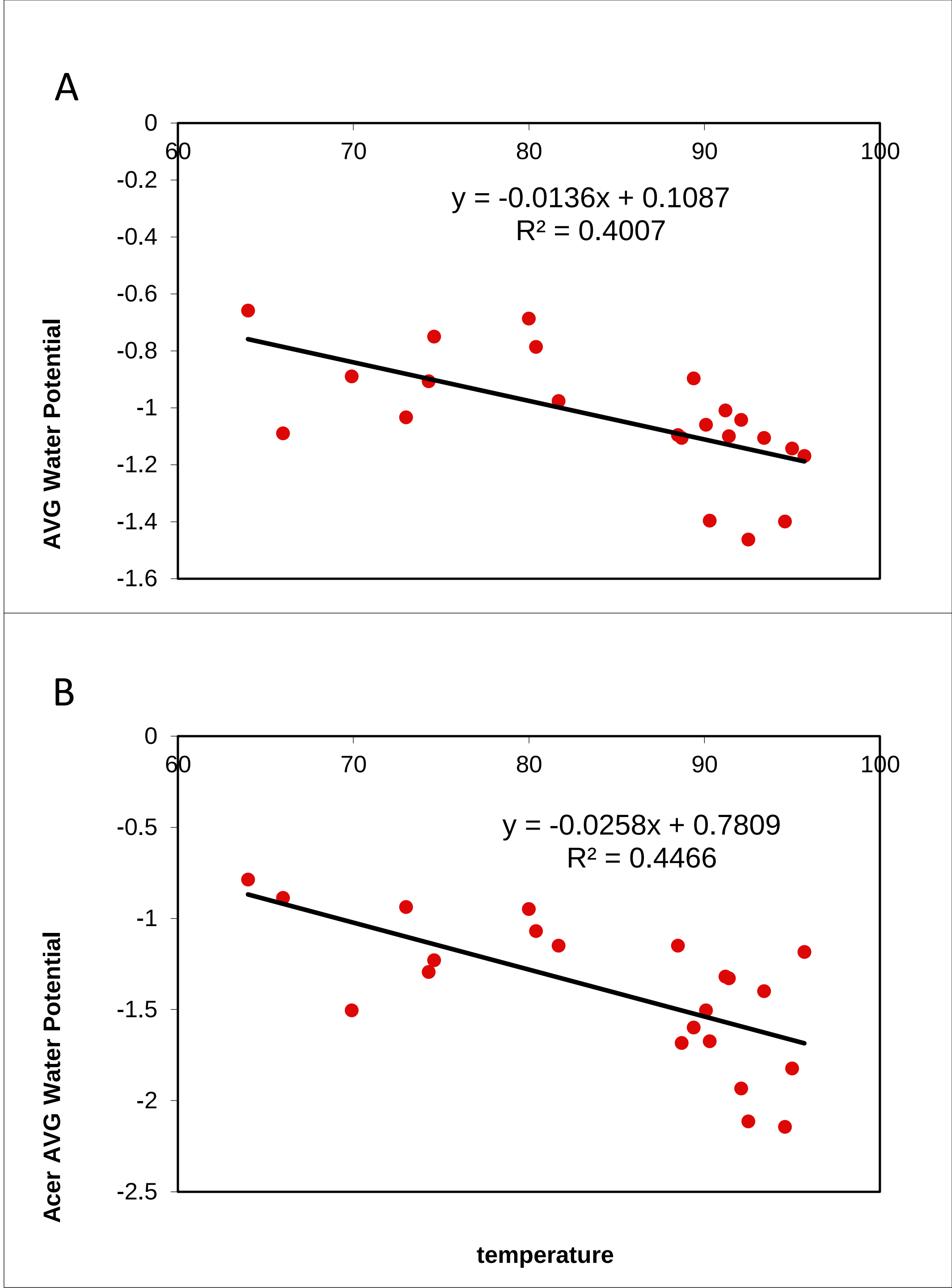


Results of Dunn's Test (Benjamini-Hochberg method)

*Indicates significant difference among samples. Upper number signifies Dunn's pairwise z test statistic

Sample	T-55	T-56	T-57	T-58
T-56	3.124719 0.0022*			
T-57	-1.094647 0.1955	-4.219366 0.0001*		
T-58	2.423703 0.0128*	-0.701016 0.2685	3.518350 0.0011*	
T-59	-0.362670 0.3584	-3.487390 0.0008*	0.731976 0.2901	-2.786374 0.0053*

Regression analyses of Ψ_{lf} and leaf temperature



Experiment 1 conclusions

- In general, through the entire growing season, *P.* × *acerifolia* had greater stomatal conductance and lower susceptibility to water stress than *A. rubrum* 'Armstrong'.
- These results suggest *P.* × *acerifolia* performs more successfully in these systems when compared to *A. rubrum.*
- These results are likely due to inherent differences in the species' physiological traits that affect water relations and may be influenced by other environmental factors that influence plant health (disease and insect pressure)

Experiment 2

- 25 trees of 13 different species/cultivars in multiple GI tree trenches and tree pits
  - Stomatal conductance

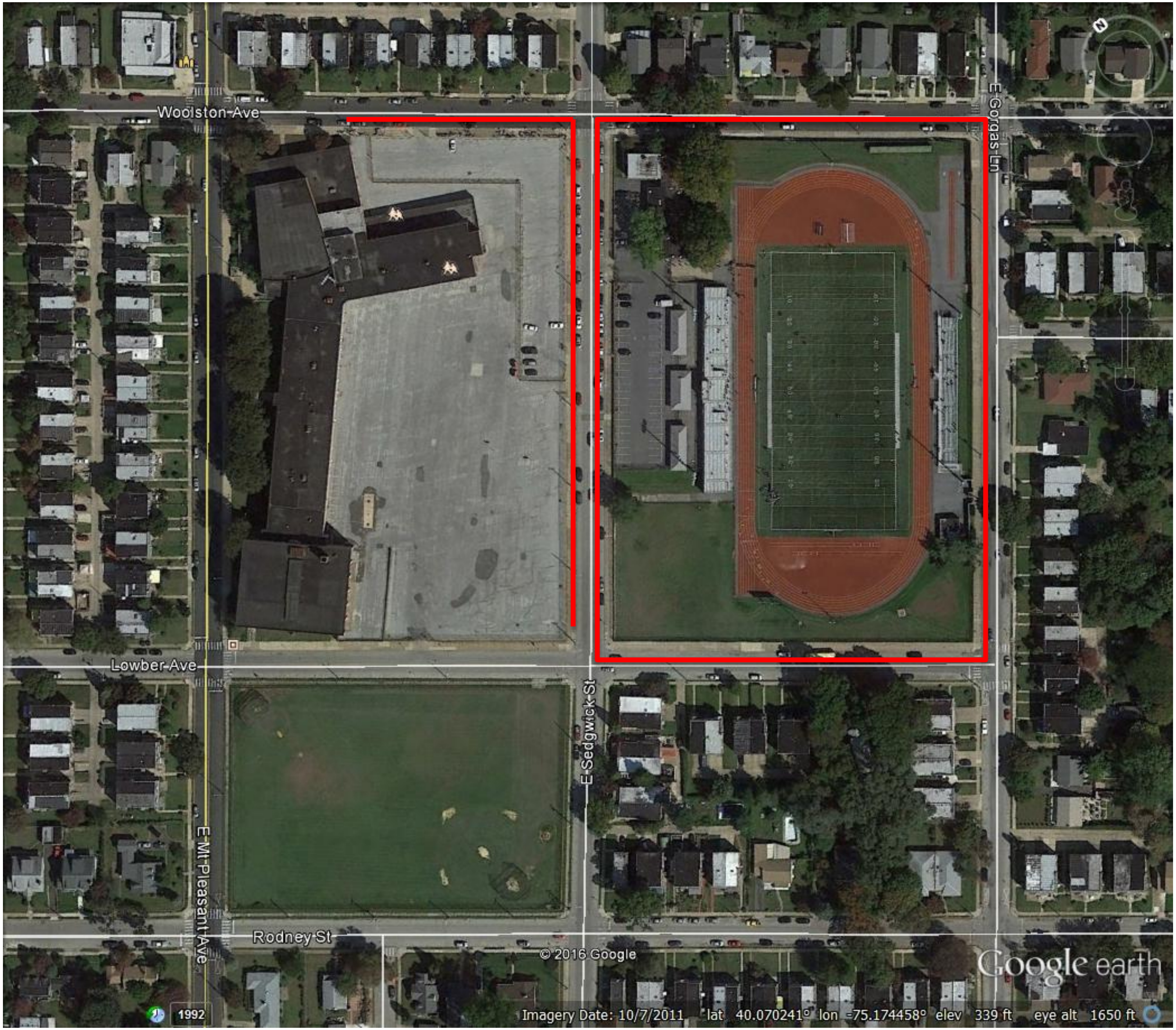
1. Assess the rate of water movement out of tree trench systems via stomatal conductance
2. Evaluate plant moisture stress of different tree species





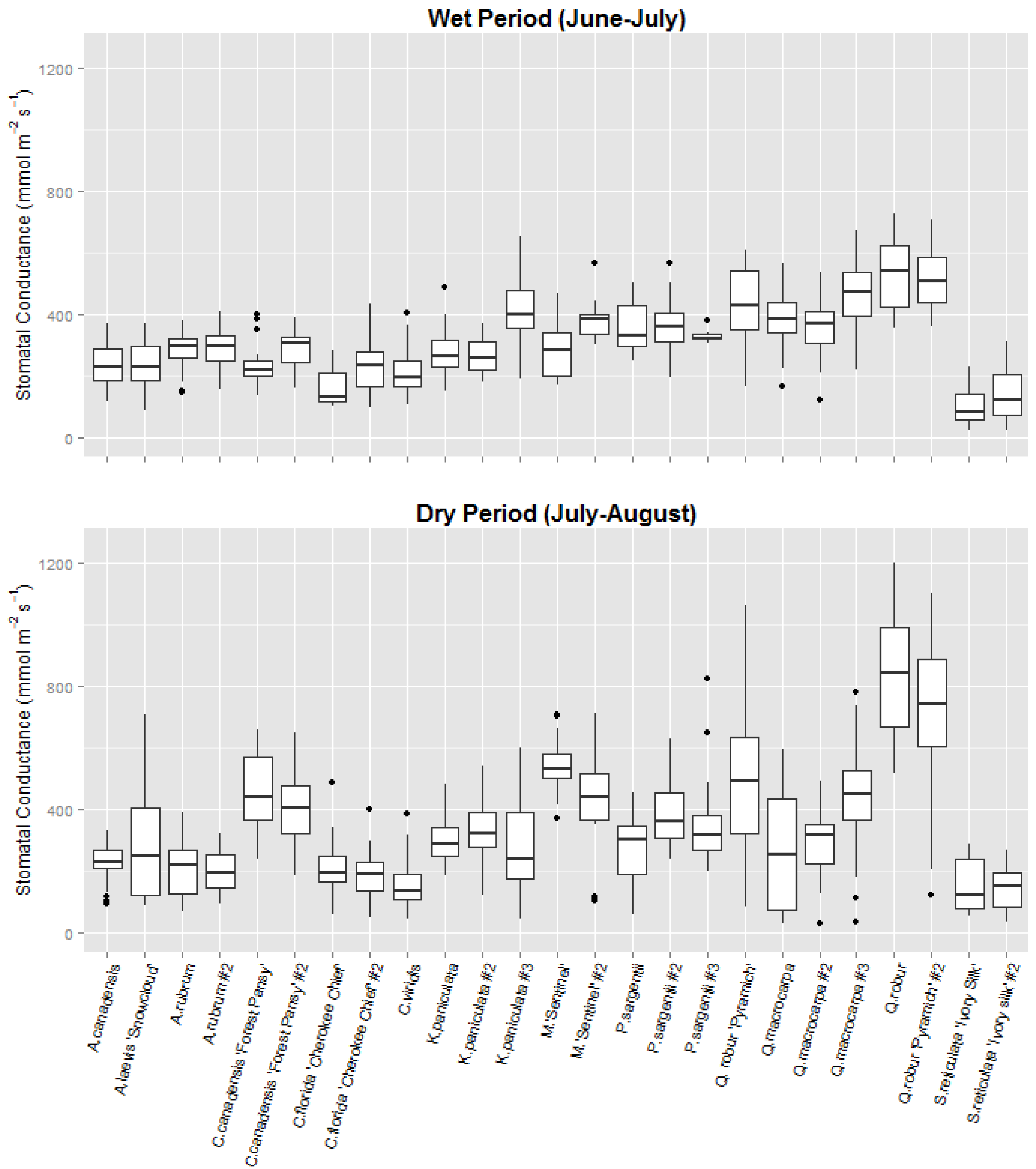

~15 species of trees being evaluated for stomatal conductance rates

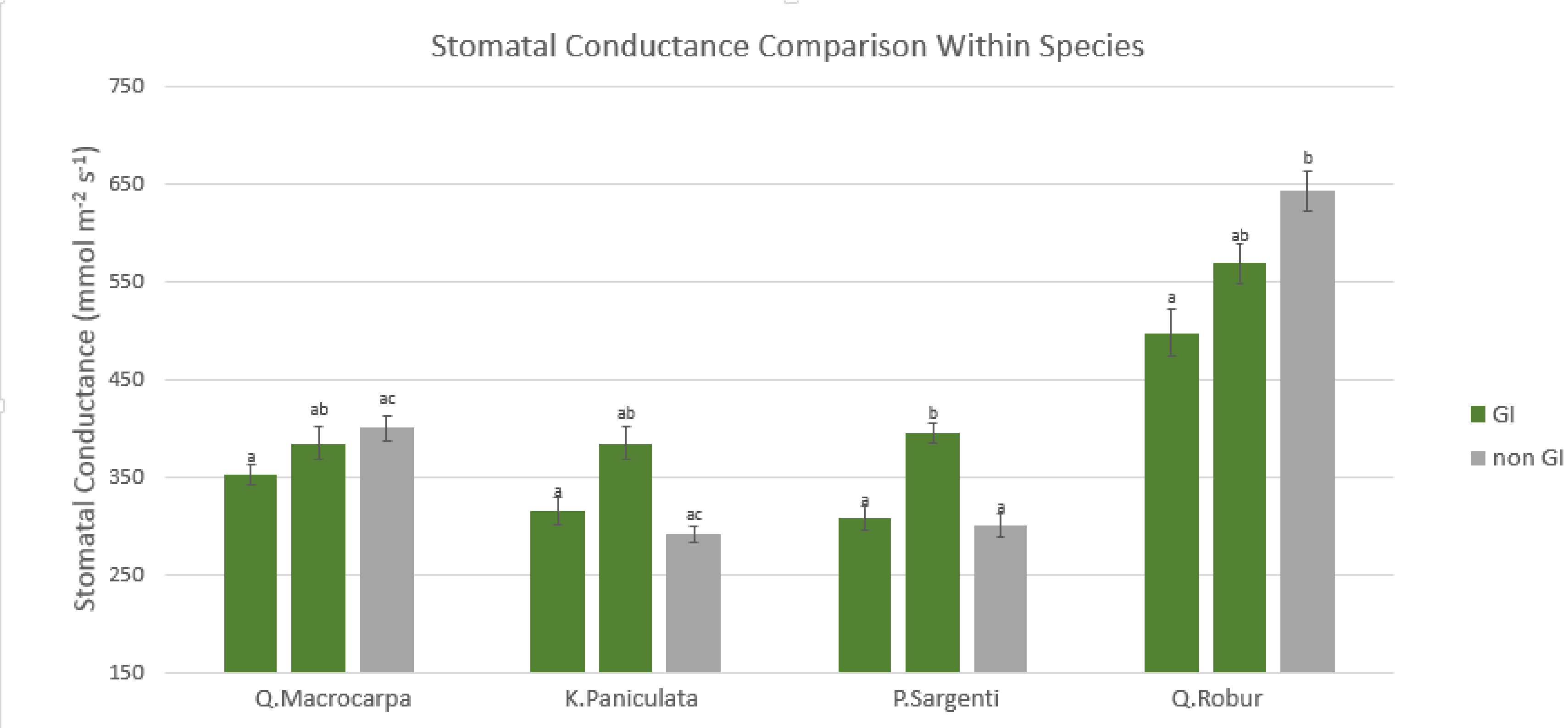
Examples*: Quercus rubra; Quercus robur*; *Cercis canadensis*; *Kolreuteria paniculata*; *Quercus macrocarpa*; *Syringa reticulata*


Woolston Ave
E Gorgas Ln
Lowber Ave
E Sedgwick St
E Mt Pleasant Ave
Rodney St
© 2016 Google
Google earth
1992
Imagery Date: 10/7/2011 lat 40.070241° lon -75.174458° elev 339 ft eye alt 1650 ft

Species respond differently in periods of high and low precipitation.

Several species exhibited resilience to water deficit through sustained or increased stomatal conductance in the dry period.





Direct comparisons of Green Infrastructure (GI) storm water trenches and traditional street pits (non GI) between individual trees of same species. Shared letters within species indicate statistical insignificance

On average, *K. paniculata* and *P. sargentii* conduct more water in GI storm water trenches whereas *Q. robur* interestingly conducted more water in a traditional street pit.

Non-parametric pairwise multiple comparisons (Dunn's test) of the average stomatal conductance of individual trees over the research duration.

	A.laevis 'Snowcloud'	M.'Sentinel'	C.viridis	M.'Sentinel'	K.paniculata	C.canadensis 'Forest Pansy'	C.canadensis 'Forest Pansy'	K.paniculata	P.sargentii	K.paniculata	Q.macrocarpa	Q.macrocarpa	P.sargentii	Q.macrocarpa	Q.robur 'Pyramich'	Q.robur 'Pyramich'	Q.robur	A.rubrum	A.rubrum	P.sargentii	A.canadensis	C.florida 'Cherokee Chief'	S. reticulata	C.florida 'Cherokee Chief'
Malus 'Sentinel'	0.0000*																							
Crataegus viridis	1	0.0000*																						
Malus 'Sentinel'	0.0000*	0.3024	0.0000*																					
Koelreuteria paniculata	0.0000*	0.1447	0.0000*	0.0005*																				
Cercis canadensis 'Forest Pansy'	0.0000*	0.5827	0.0000*	0.0074*	1																			
Cercis canadensis 'Forest Pansy'	0.0000*	0.3335	0.0000*	0.0016*	1	1																		
Koelreuteria paniculata	0.0001*	0.0024*	0.0002*	0.0000*	1	0.2623	0.2796																	
Prunus sargentii	0.0000*	0.0748	0.0000*	0.0001*	1	1	1	1																
Koelreuteria paniculata	0.0000*	1	0.0000*	0.2335	0.0801	0.423	0.205	0.0004*	0.0331															
Quercus macrocarpa	0.0000*	1	0.0000*	0.605	0.0306	0.1979	0.0822	0.0001*	0.0111*	1														
Quercus macrocarpa	0.0000*	1	0.0000*	0.0865	0.2529	0.9605	0.5859	0.0040*	0.1366	1	1													
Prunus sargentii	0.0000*	0.8478	0.0000*	1	0.0030*	0.0331	0.0087*	0.0000*	0.0007*	0.7418	1	0.3159												
Quercus macrocarpa	0.0000*	0.9778	0.0000*	1	0.0024*	0.0325	0.0070*	0.0000*	0.0004*	0.8514	1	0.345	1											
Quercus robur 'Pyramich'	0.0000*	0.0121*	0.0000*	0.7443	0.0000*	0.0001*	0.0000*	0.0000*	0.0000*	0.0054*	0.0298	0.0013*	0.1757	0.0793										
Quercus robur 'Pyramich'	0.0000*	0.0000*	0.0000*	0.0051*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0001*	0.0000*	0.2039									
Quercus robur	0.0000*	0.0000*	0.0000*	0.0001*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0232*	1								
Acer rubrum	0.0263	0.0002*	0.1017	0.0000*	0.1703	0.0311	0.0298	0.7552	0.1845	0.0000*	0.0000*	0.0003*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*							
Acer rubrum	0.1297	0.0000*	0.4526	0.0000*	0.0332	0.0042*	0.0033*	0.1937	0.0331	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	1						
Prunus sargentii	0.0001*	0.0069*	0.0003*	0.0000*	1	0.3922	0.4368	1	1	0.0017*	0.0004*	0.0121*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.7083	0.1928					
Amelanchier canadensis	1	0.0000*	1	0.0000*	0.0000*	0.0000*	0.0000*	0.0003*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0887	0.3774	0.0005*				
Cornus florida 'Cherokee Chief'	1	0.0000*	1	0.0000*	0.0000*	0.0000*	0.0000*	0.0002*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0415	0.1904	0.0003*	1			
Syringa reticulata 'Ivory Silk'	0.4372	0.0000*	0.0264	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0001*	0.0008*	0.0000*	0.0742	0.3379		
Cornus florida 'Cherokee Chief'	1	0.0000*	1	0.0000*	0.0003*	0.0000*	0.0000*	0.0020*	0.0002*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.1904	0.6355	0.0027*	1	1	0.0618	
Syringa reticulata 'Ivory silk'	0.2737	0.0000*	0.0096*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0000*	0.0003*	0.0000*	0.0332	0.2056	1	0.0299

Dunn's test revealed the stomatal conductance of many trees significantly differed through the year (Figure 1)

Experiment 2 conclusions

- In assessing 25 different trees, the mean ranks of conductance data by species were significantly different, suggesting some species may be better suited for use in urban GI trench trees than others.
- Two potential benefits of these species are
  - 1) they have higher overall levels of conductance resulting in greater water movement out of the system via evapotranspiration following rain events, and
  - 2) they may be less susceptible to water stress during periods of low precipitation.
- Pairwise comparisons revealed that *Koelreuteria paniculata* and *Prunus sargentii* trees conducted significantly more water on average within storm water trenches compared to traditional, isolated tree pits, whereas *Quercus macrocarpa* and *Q. robur* showed the opposite tendency

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