Multiple lines of evidence to decrease drainage to surface area ratio for effective bioinfiltration stormwater control

Thomas P. O'Connor, P.E., BCEE

Environmental Engineer

ORD, CESER, WID

Edison, NJ

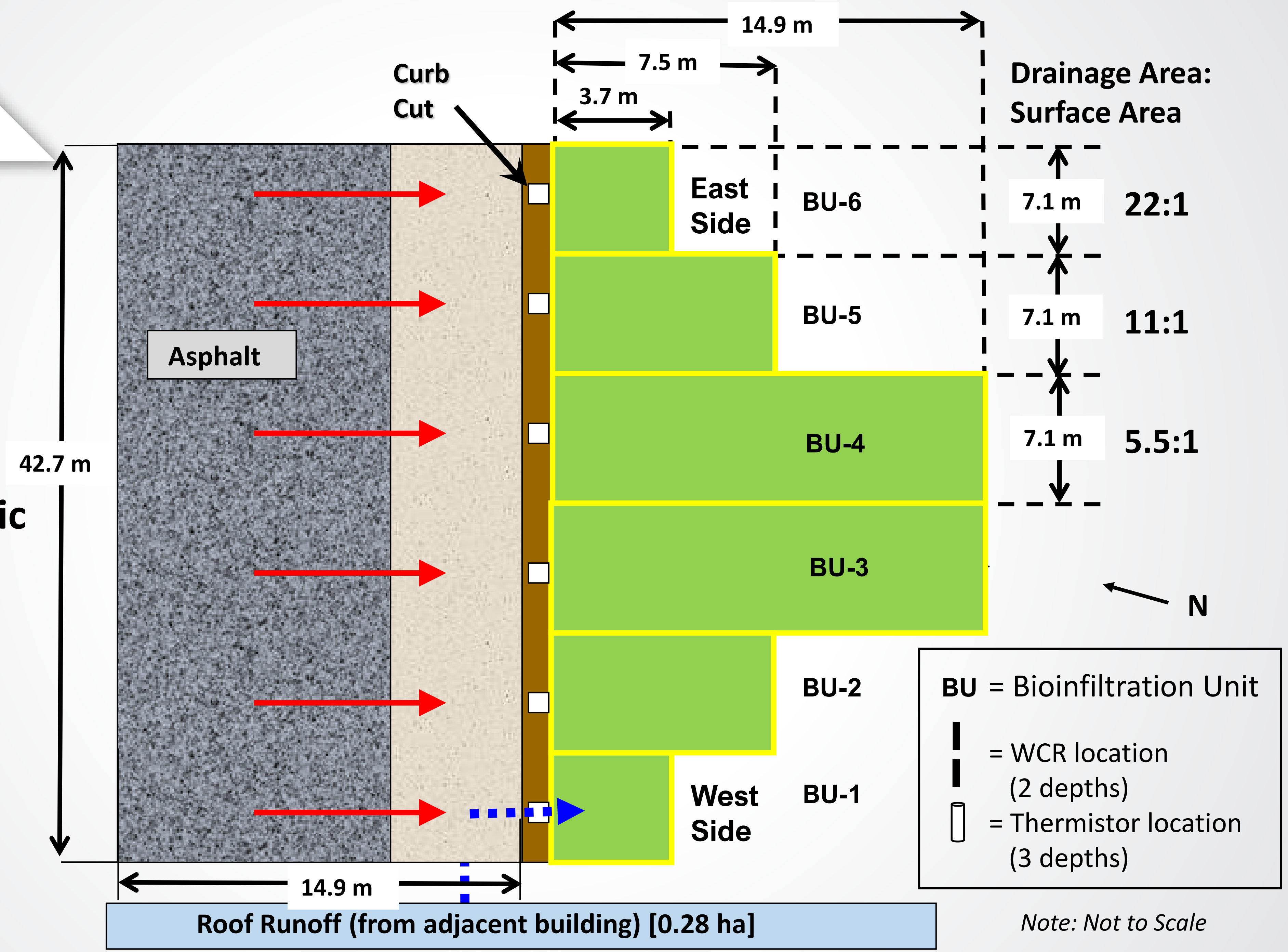
EPA Bioinfiltration Research and Demonstration Controls

- Adjacent to Permeable Pavement Research and Demonstration site
- Receives runoff from parking lot and nearby roof
- Instrumented with water content reflectometers (WCR) based on time domain reflectometer (TDR) technology
- Growing media primarily sand amended with peat moss
  - choice after extensive testing
- Plants: native, drought, inundation and salt tolerant
- Six side-by-side units – three surface areas in duplicate
  - smallest 26 m^2, middle 53 m^2 and largest 106 m^2
- Plastic (HDPE) vertical sheeting to ~ 1.2 m depth
  - separates units from each other and surrounding area

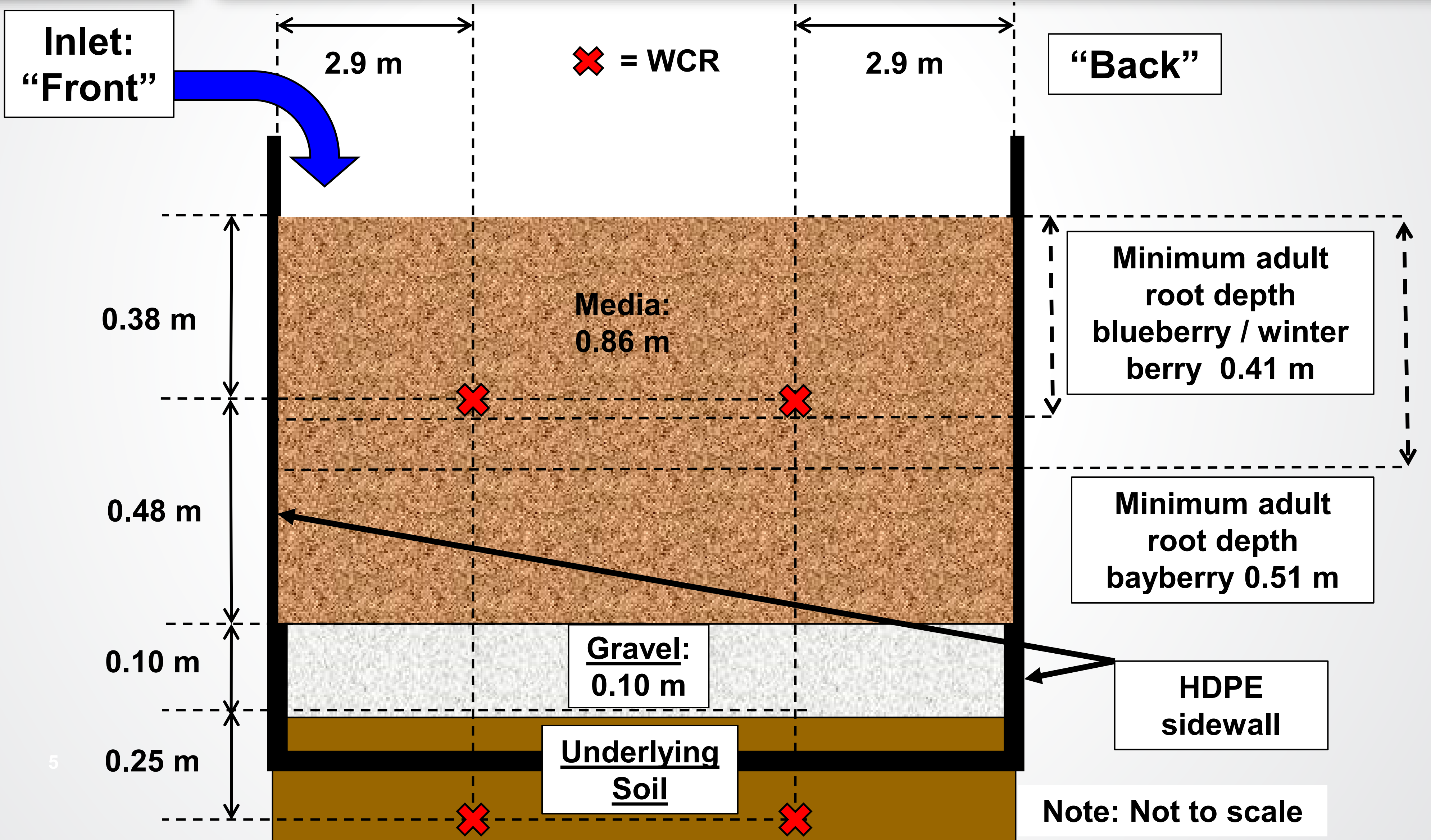
Drainage area to surface area ratio

- Experimental design to evaluate drainage to surface area ratio for sizing of bioinfiltration/bioretention control.
- At time of experimental design, regulatory guidance ranged from ~ 2.5:1 to 33:1 (Stander et al. 2010).
- Drainage area for each bioinfiltration unit ~571 m^2 comprised of roof (465 m^2) and asphalt runoff (105 m^2).
- Middle unit 11:1 drainage to surface area ratio
  - at time closest to local guidance (NJDEP 2007)
- Smallest unit 22:1 drainage to surface area ratio
- Largest unit 5.5:1 drainage to surface area ratio

Plan View Schematic



Media 90% sand (United States Golf Association concrete sand) and 10% sphagnum peat moss by volume.
Organic content 1.1% tested by lost on ignition.

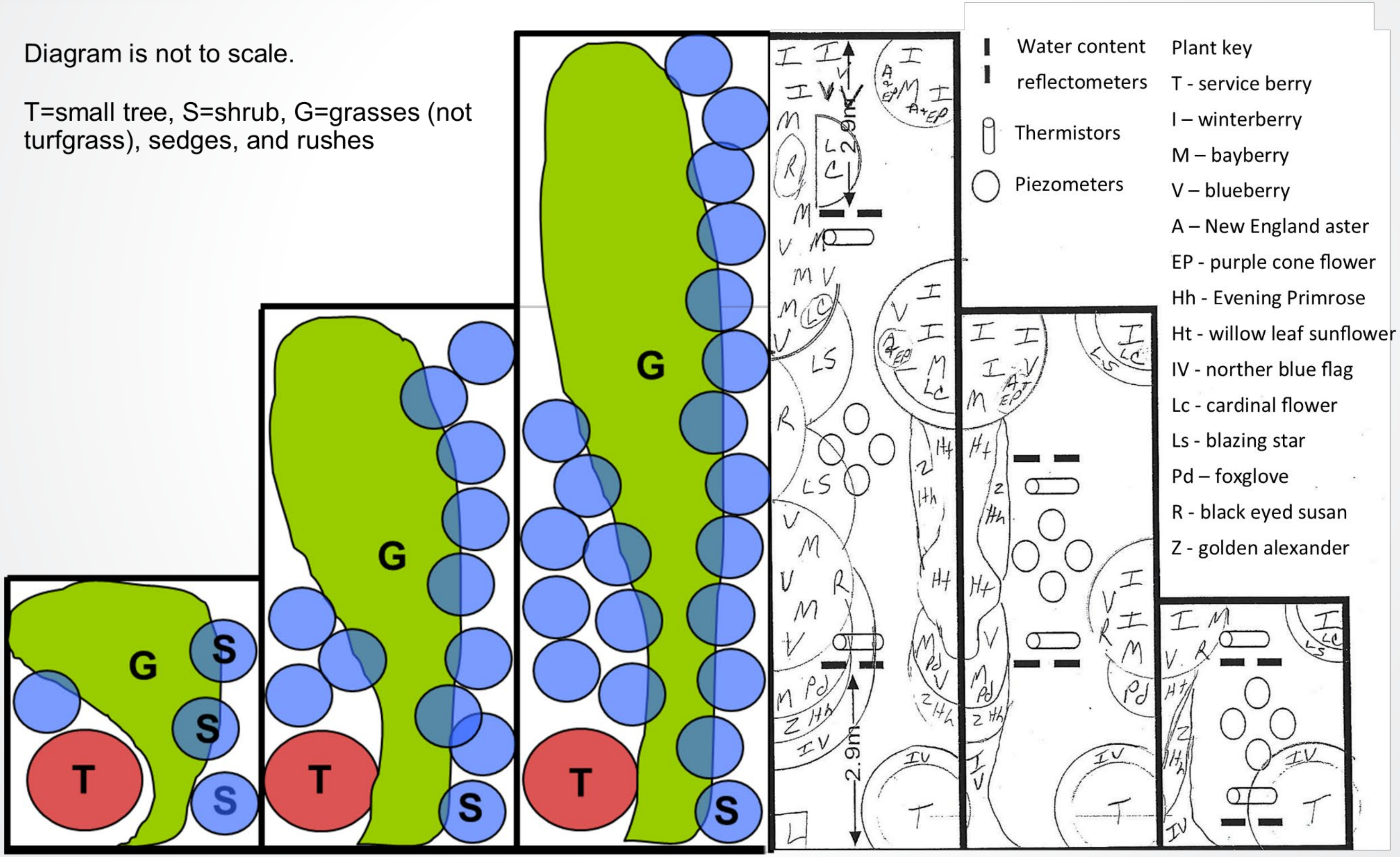


Bioinfiltration units during construction

Plant planning diagrams with location of instrumentation

Diagram is not to scale.

T=small tree, S=shrub, G=grasses (not turfgrass), sedges, and rushes



Bioinfiltration units over time before initial survey

5/3/2010

6/11/2010

5/15/2012

11/1/2012

Assessment of shrub growth

- Conducted December 2012
  - Documented plant survival
  - Calculated Basal area (BA) for diameters at three heights
    - base [~0.05 m - similar to root collar]
    - 0.6 m
    - 1.4 m [DBH – Diameter at Breast Height]
  - Measured height
- Reviewed ancillary data for period since planting
  - Monthly rainfall
  - Calculated local reference crop evapotranspiration
  - Soil moisture from WCR
- Results published in ASCE Journal (Brown et al., 2015)

Number of shrubs per bioinfiltration unit (BU)

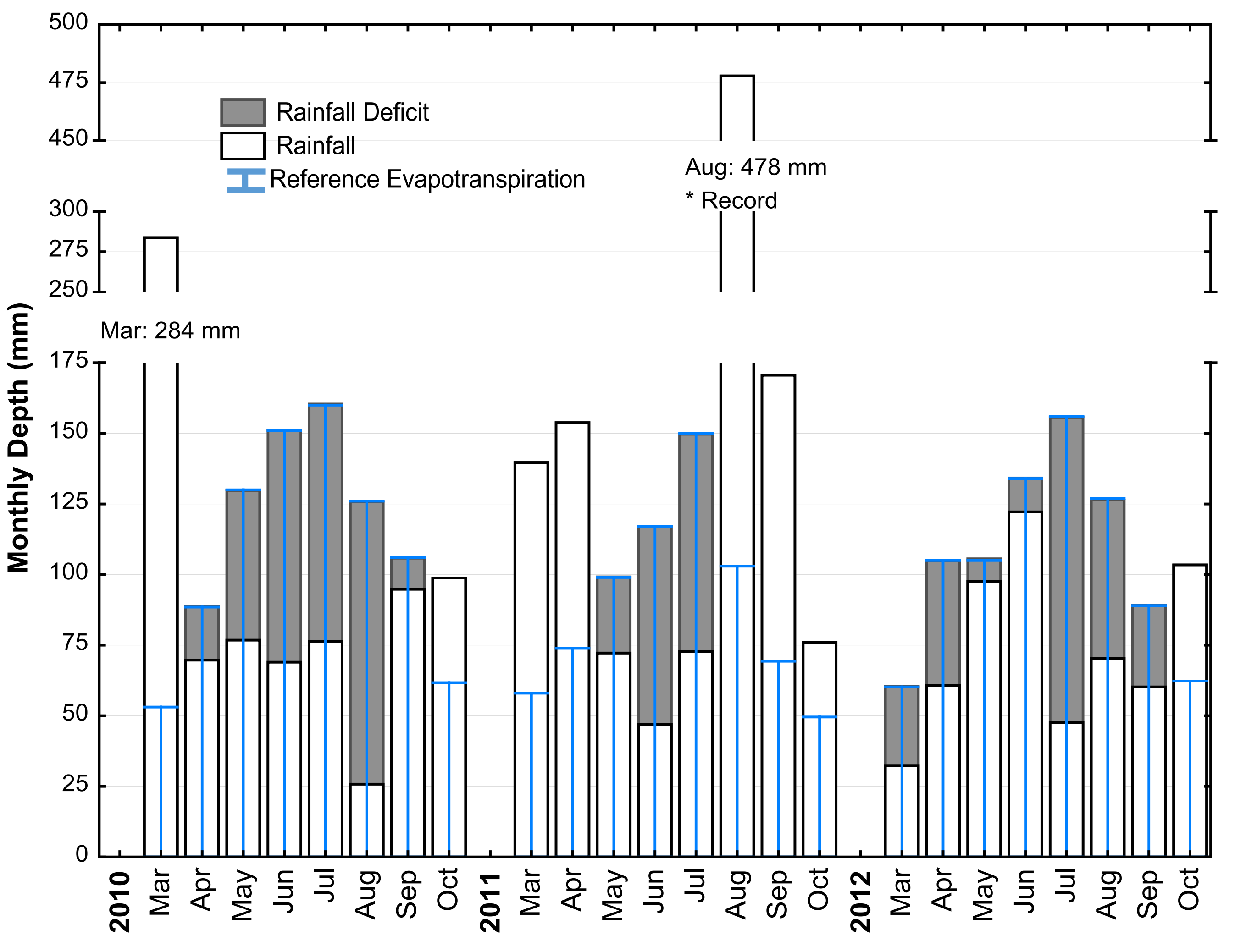
Some plants did not survive

BU number	BU size	Location	Number measured (planted-2010)		
			Bayberry	Blueberry	Winter-berry
1	Small	West	1 (1)	1 (1)	2 (2)
2	Medium	West	3 (3)	3 (3)	6 (6)
3	Large	West	9 (11)	9 (11)	6 (7)
4	Large	East	9 (11)	11 (11)	6 (7)
5	Medium	East	3 (3)	1 (3)	5 (6)
6	Small	East	1 (1)	1 (1)	2 (2)

Brown et al. 2015

Rainfall and reference crop evapotranspiration (ET_0)

Monthly ET_0 –
Monthly Rainfall
= Rainfall Deficit



Record August 2011 Rainfall Includes Hurricane Irene

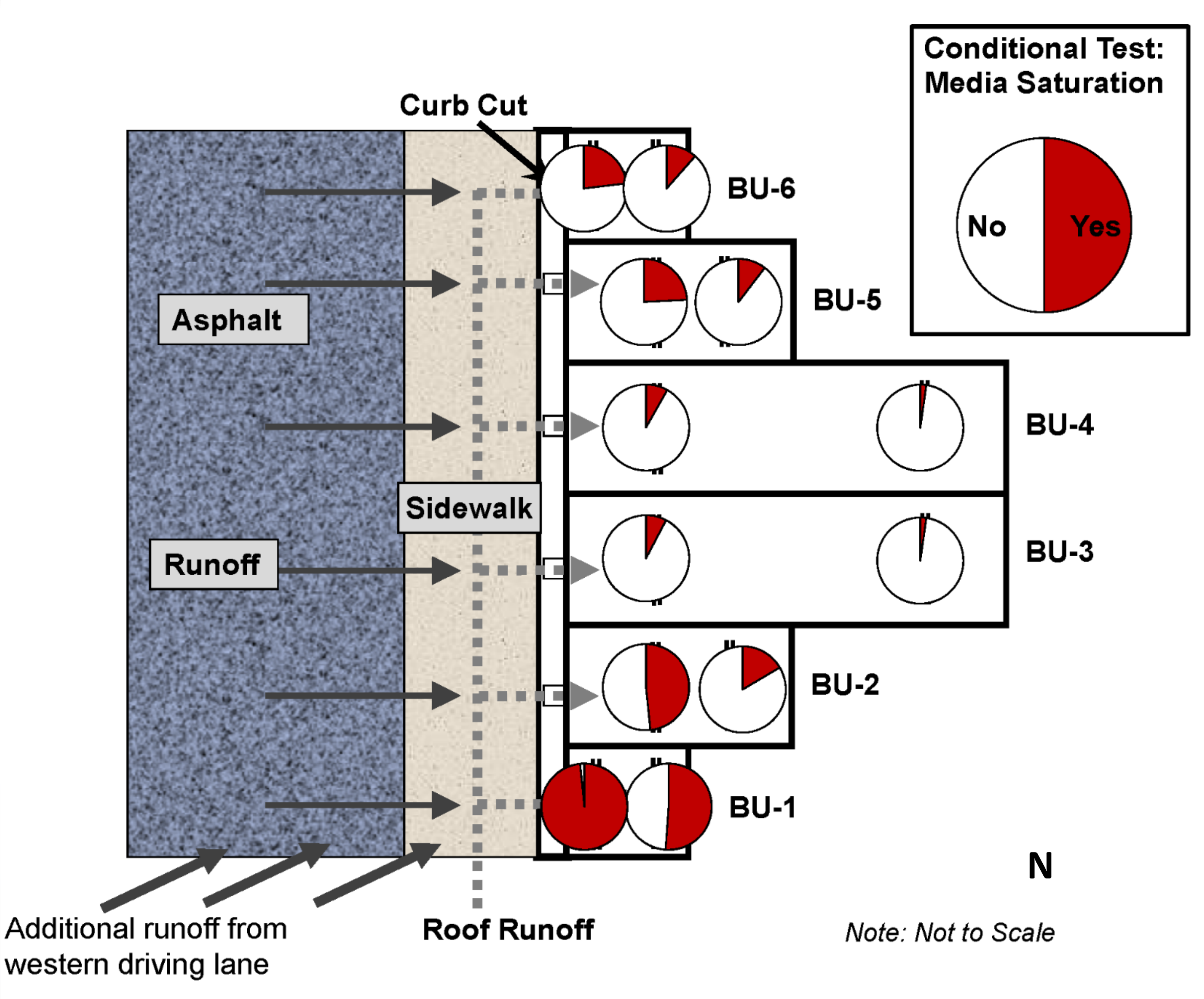
Brown et al. 2015

WCR monitoring locations media saturation

Total of 91 events analyzed with complete data from all WCR locations.

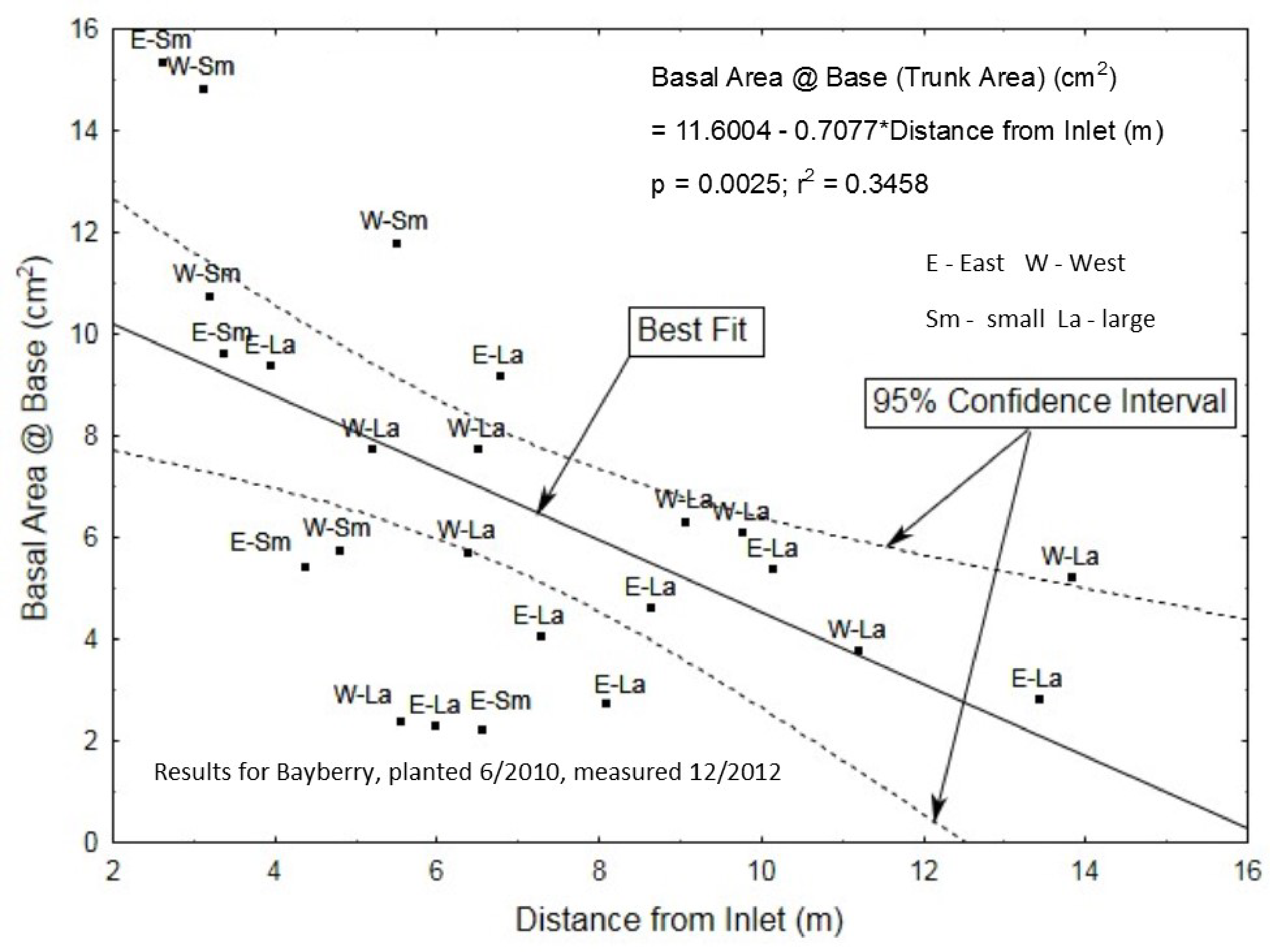
Period of analysis: 2010-2012 growing seasons (April to October).

When saturation not frequent, change in soil moisture attributed to direct rainfall.



Brown et al. 2015

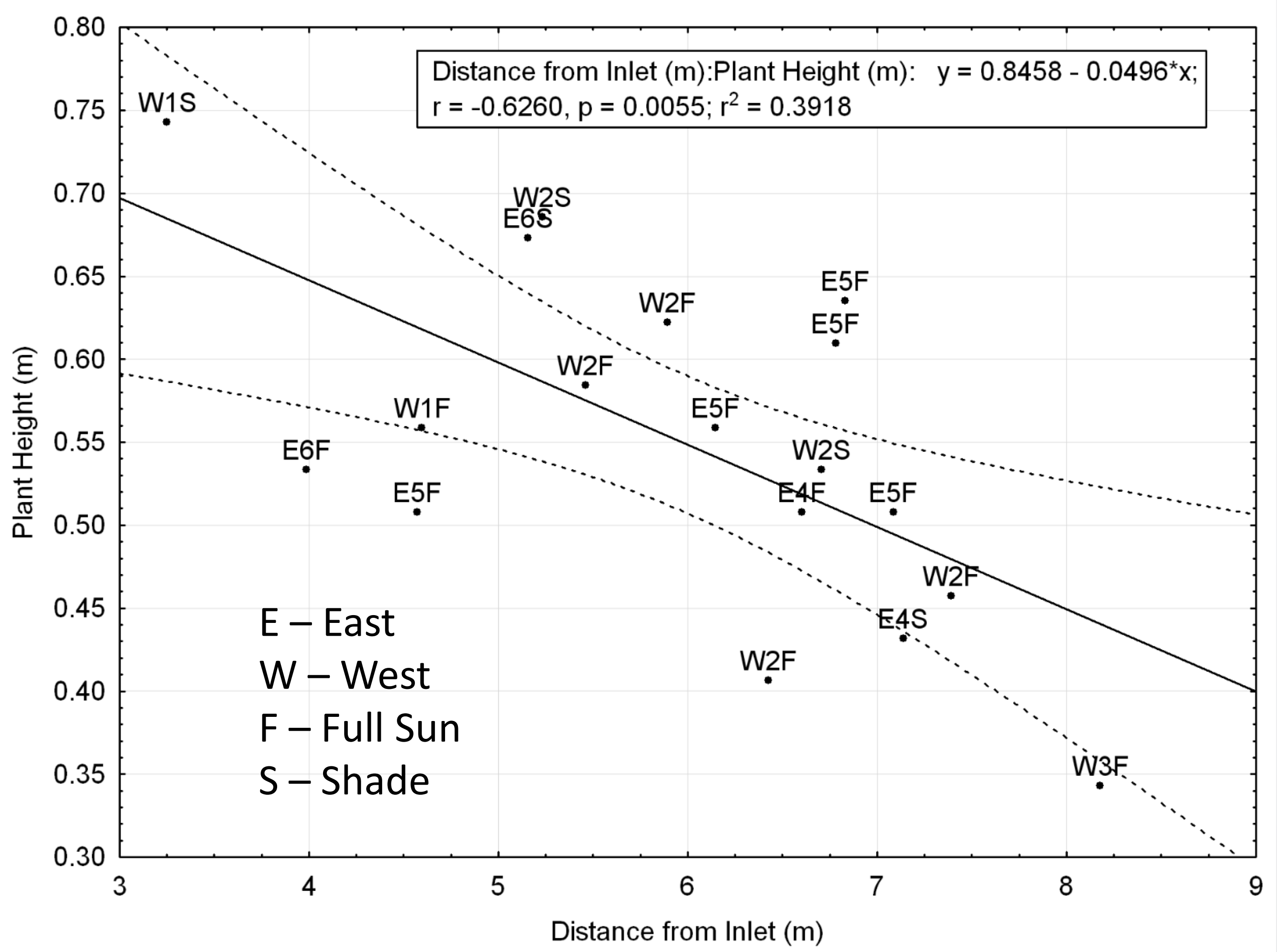
Basal area larger for bayberries closer to inlet and in smaller bioinfiltration units



Brown et al. 2015

Winterberry is taller closer to inlet and in smaller bioinfiltration units

Brown et al. 2015



Conclusion and discussion for initial shrub study

- Surface infiltration not uniform
- Rain fall deficit during growing season:
  - Results in plants away from front (runoff inlet) not getting enough water
- Smaller bioinfiltration controls provide better plant function than larger controls:
  - Greater plant survivability and robustness
- Smaller biofiltration controls continue to infiltrate even when flooded
  - continued performance even at smaller size

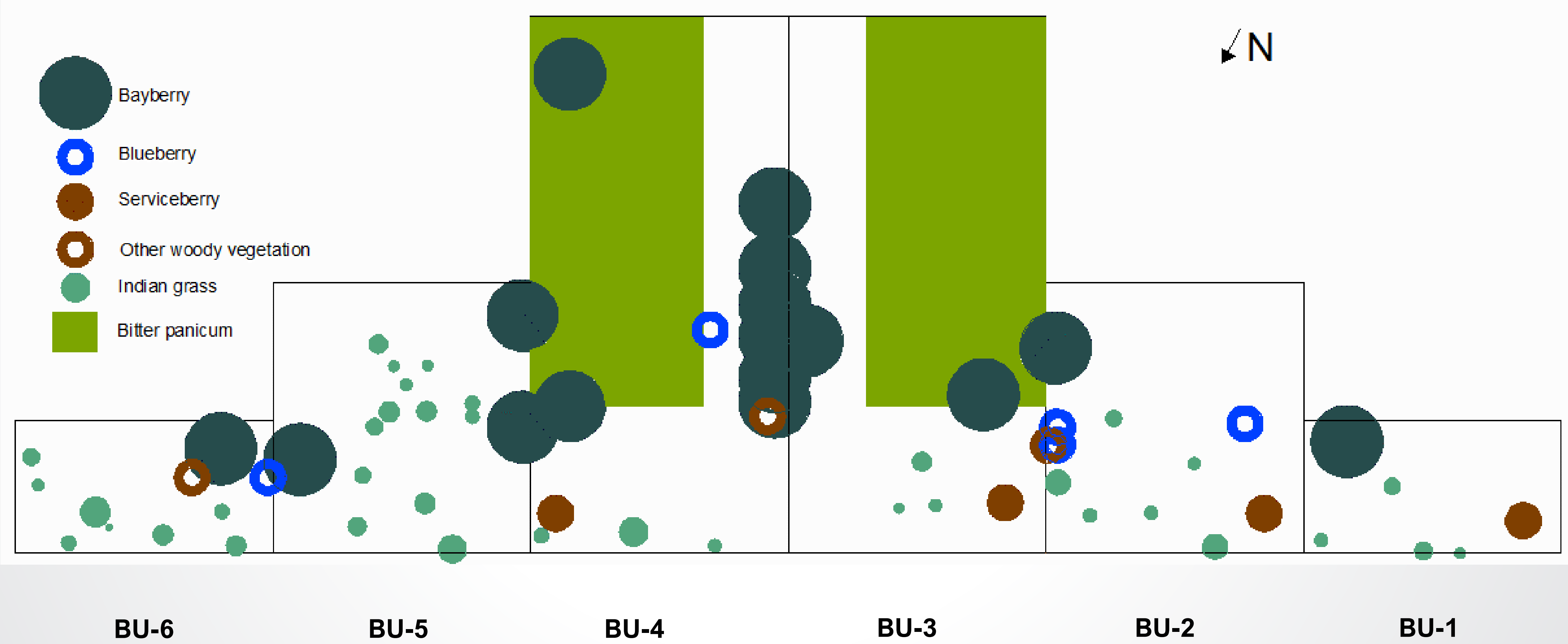
Brown et al. 2015

Follow-up plant survey and analysis of planting media

- Plant survey conducted June – August 2018
- Measured two dominant grass species:
    - *Sorghastrum nutans L.* (Indiangrass) BA at 10 -15 cm
    - Coverage of *Panicum amarum Ell.* (bitter panicum)
- Shrubs and woody vegetation at DBH (1.4 m) only
- Height of shrubs and other woody vegetation
- Identification of new (unplanted) woody vegetation
- Analysis of planting media samples:
    - Organic content tested by loss on ignition (LOI)
    - Phosphorous extraction and colorimetric method
- Assessment of construction material cost

Bioinfiltration units in August 2018

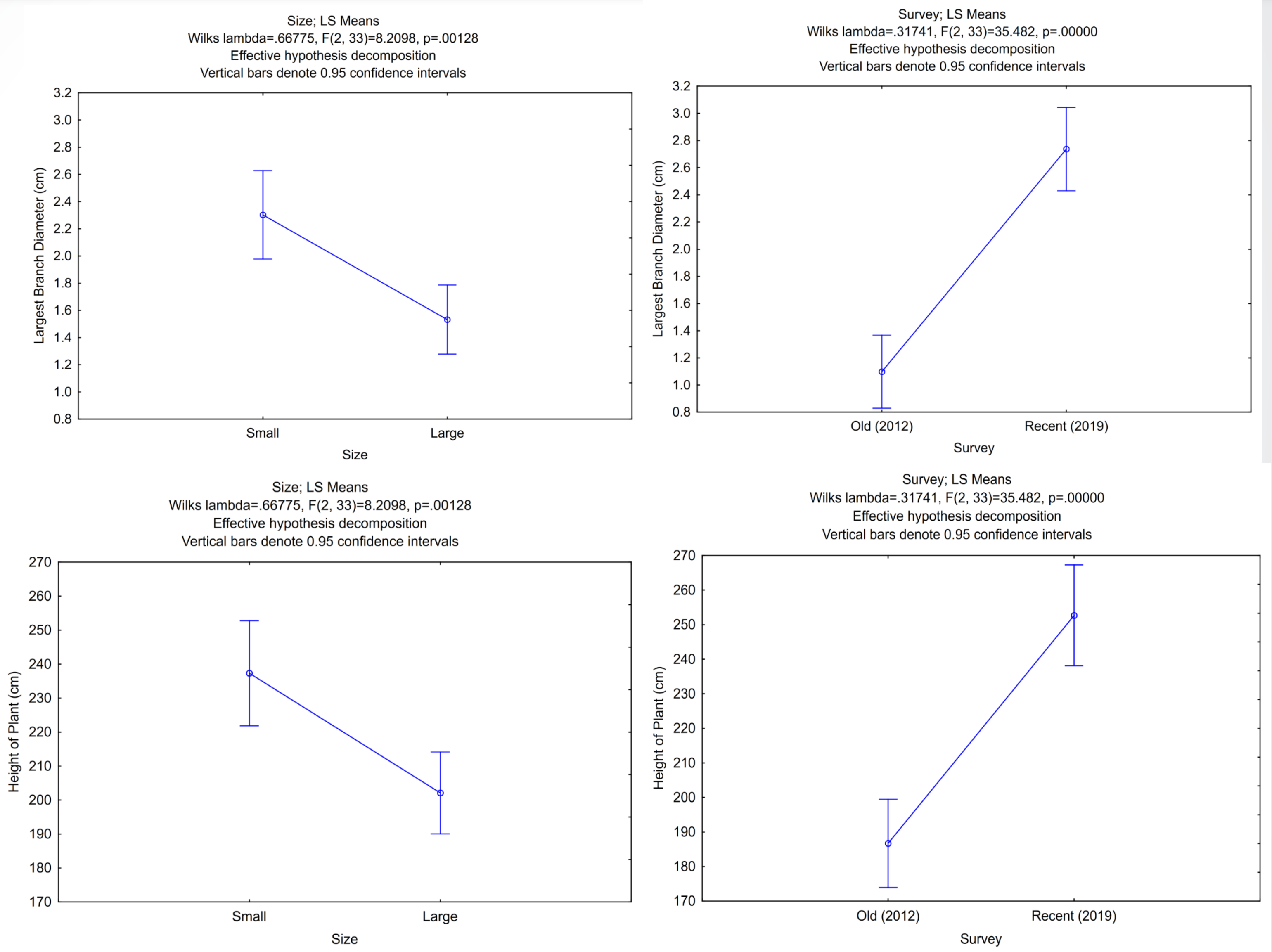
Shrub and woody vegetation and grass distribution



Grass Basal area (Indiangrass) and coverage area (bitter panicum) are to scale.

Statistical Analysis Multivariate ANOVA for Bayberry

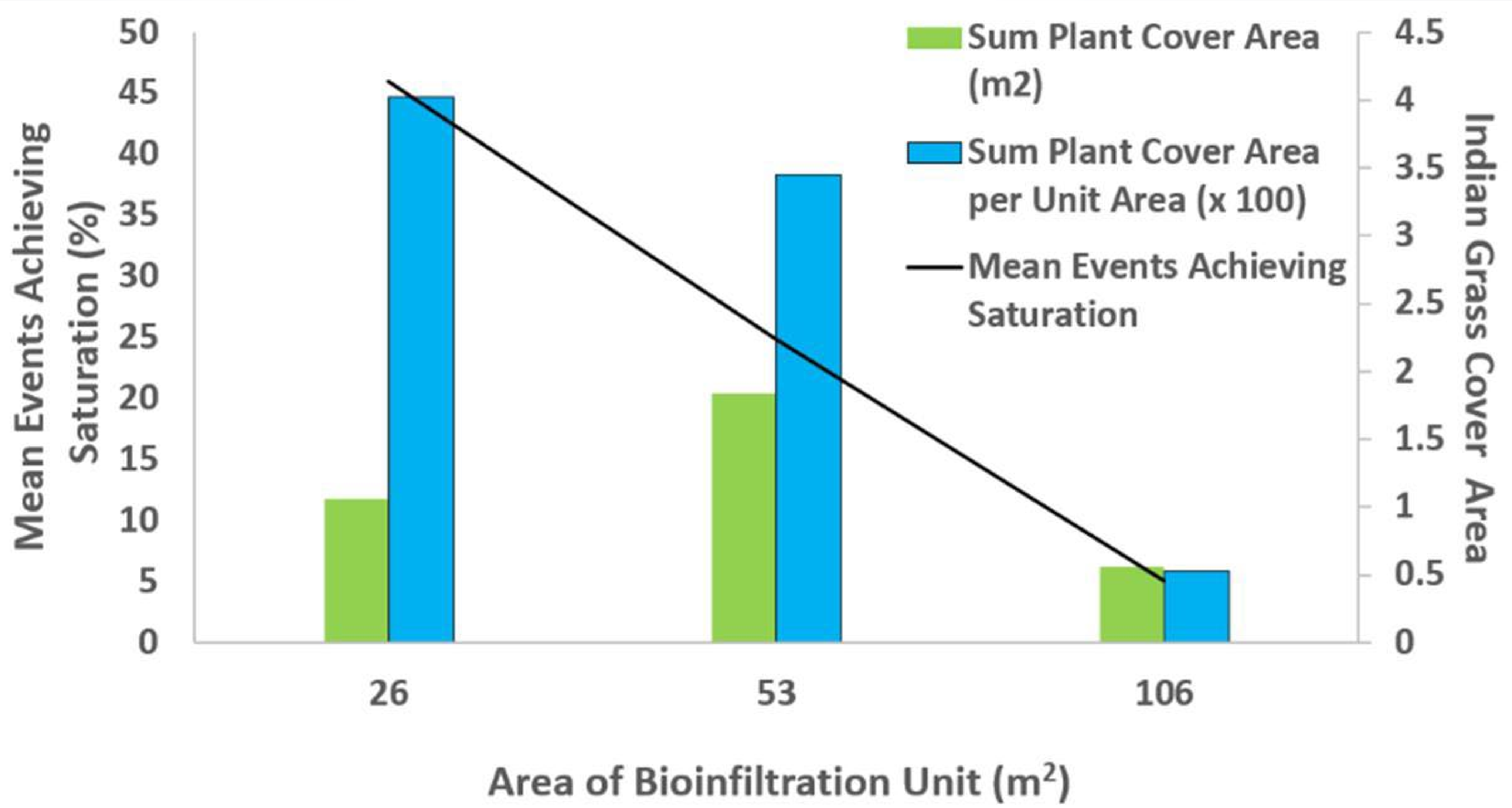
- Multivariate Analysis of Variance (MANOVA)
  - Bayberry largest branch diameter (cm) and height (cm)
  - Categorical: BU sizes (Small & Large) and survey (Old & Recent)



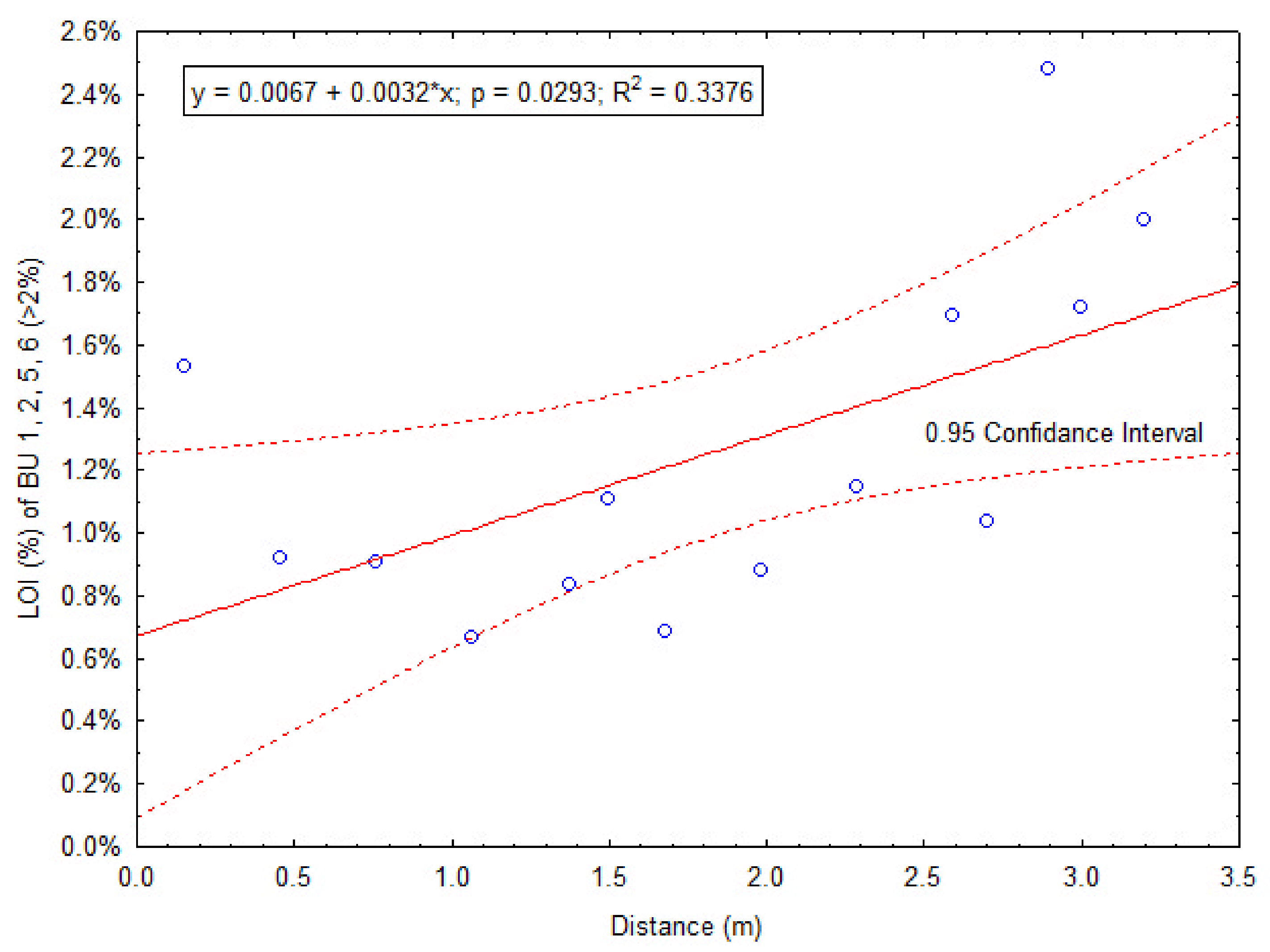
2018 plant survey observations and media analysis

- Results consistent with previous findings: smaller controls have more robust plant growth
- Bayberry taking over, no winterberry observed
- New (unplanted) trees observed towards inlets
  - Two black cherry and a common mulberry.
- Grasses indicative of previous soil moisture evaluation:
  - Indiangrass dominates smaller BU and near inlet
  - Bitter panicum (aka beach grass) dominates away from inlet in largest BU, relying on direct rainfall
  - Indiangrass "best in deep, well-drained floodplain soils" (USDA)
  - Bitter panicum adapted to "low soil moisture"(USDA)
- Organic matter and phosphorous building up in top layer and smaller units and toward inlet

Indiangrass cover per surface area compared to percent events achieving saturation

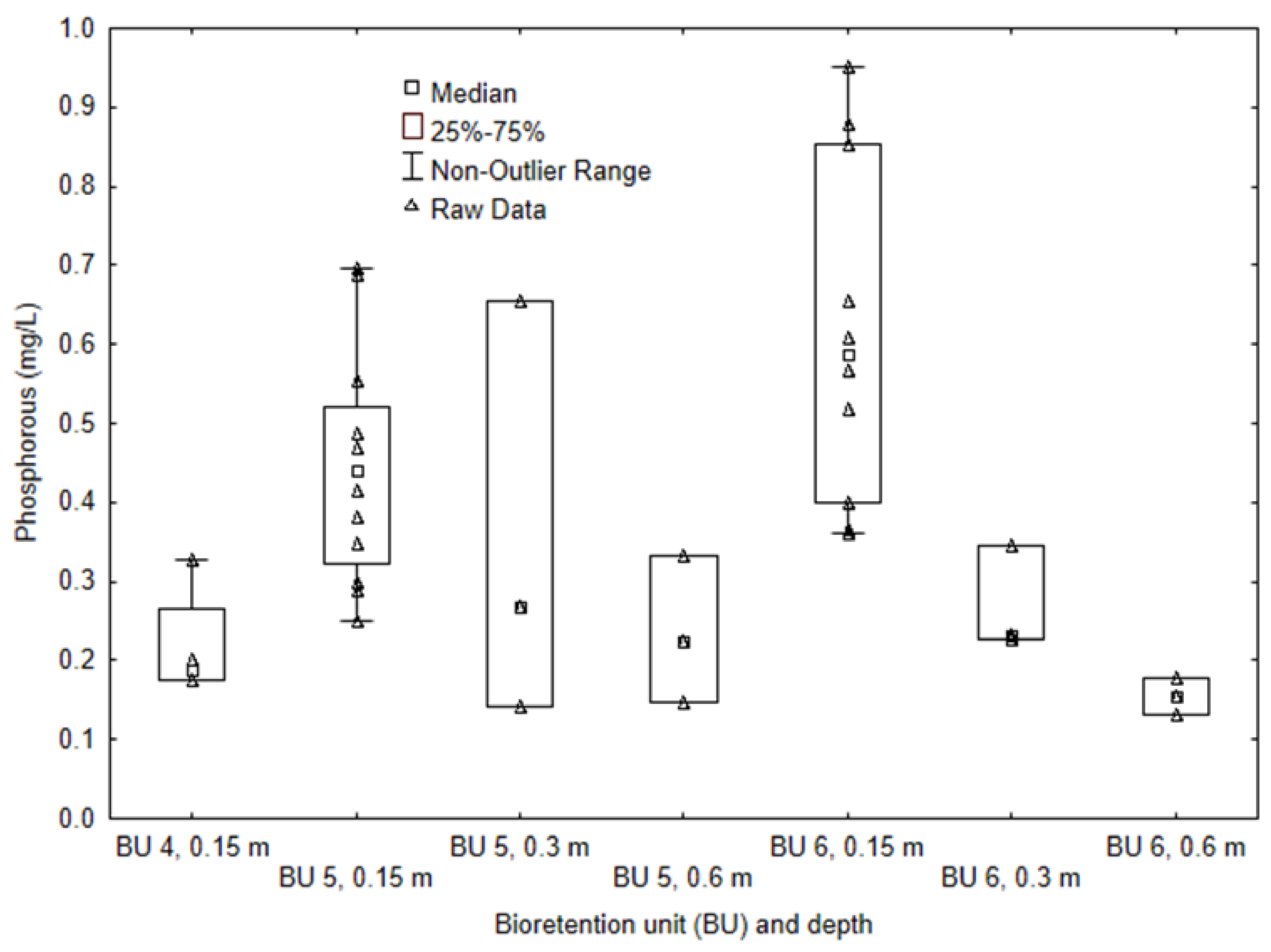


Regression of loss on ignition values of planting media peaks about 3 m from influent



Phosphorous box plots grouped by bioinfiltration unit and depth

Similar result to LOI; high correlation (0.78) between LOI and phosphorous



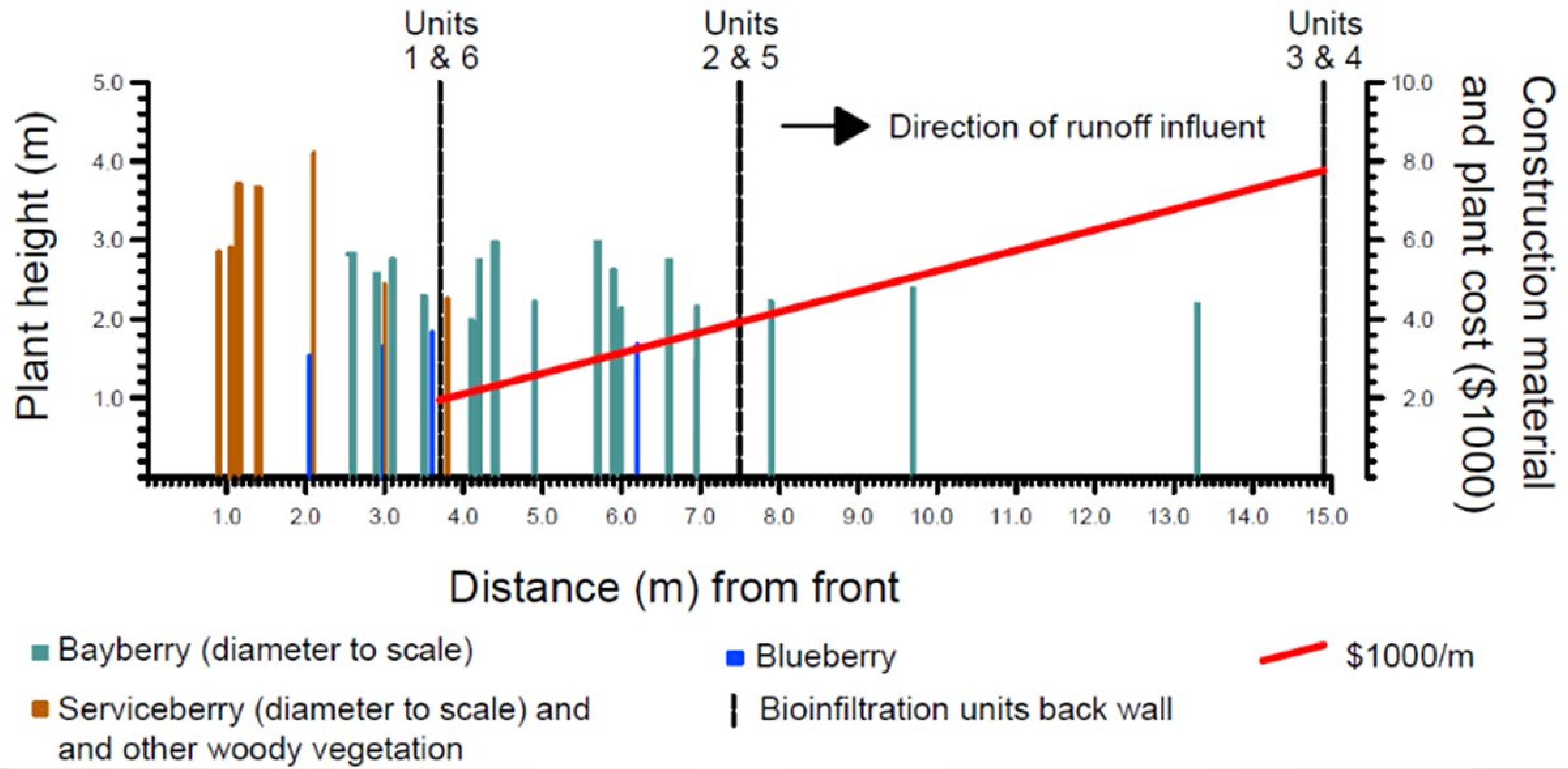
Costs[1] of construction materials and plants for bioinfiltration units

Bioinfiltration unit size	Engineered Media[2]	Mulch	Geotextile	Plants as installed	Total	Percentage cost of engineered media
Smallest	$1,440	$38	$57	$438	$1,970	73%
Medium	$2,890	$78	$114	$822	$3,910	74%
Largest	$5,780	$154	$228	$1,633	$7,798	74%

[1]As built construction costs from 2009; plant costs from 2010.

[2]State or Municipal specified bioretention planting media will be similar or more expensive in cost though specified depth may be less.

Increasing cost and less plants achieving DBH (1.4m) with surface area over design



Extent of surface flow typical storm

Results other bioretention and stormwater control studies

- Bioretention:
  - Ayers and Kangas (2018) observed organic matter accumulating in top 10 cm; recommended confining organic amendments to top layer only and minimizing other amendments due to leaching of nutrients.
  - Tu et al. (2020) concluded trees planted in tree trench systems depended on rainfall only; over designed infiltration beds did not supply water to trees.
  - Brown and Hunt (2012) indicated infiltration during storms as important component of control process.
- For other stormwater controls Lee et al. (2015) and Razzaghmanesh and Borst (2019) observed sidewall exfiltration as predominant component of infiltration.

Why bother with bioinfiltration/bioretention – engineering perspective

- Water Quality (not flood control)
  - Treatment at source – Low Impact Development (LID)
- Non-water quality factors:
  - Can be placed in municipal right-of-way (ROW)
  - Excavated soil pit (hole): safety or structural issues, i.e., fall potential or sidewall collapse (fill it in with sand)
- Stormwater and urban heat island (UHI) design example
  - For stormwater quality - bioretention upstream of storm drain inlet
  - For UHI – to shade paved area, tree pit every 20 - 40 curb ft (EPA, undated)
  - For 200 ft street with sewer inlet on each side, put in one bioretention with tree for each side of street upstream of inlet and 4 to 8 tree pits for UHI for each side of street (as driveways and utilities allow)

Better Design of Bioretention

- Maximize return on investment
- Size to engage entire surface area of bioretention and attain full volume control more often resulting in better plant growth and increased pollutant removal
- Use lowest percentage of organic amendments as per local guidance as bioretention will accumulate organic matter and phosphorous in the upper layer
- Most recent local guidance (NJDEP 2021) design example has a 21:1 drainage to surface area ratio (similar to smallest unit design of 22:1 for Edison)

EPA References

- R. Brown, T. P. O'Connor and M. Borst (2015). "Divergent Vegetation Growth Patterns Relative to Bioinfiltration Unit Size and Plant Placement" ASCE's Journal of Sustainable Water in the Built Environment (JSWBE), Vol. 1, No. 3. (http://ascelibrary.org/doi/abs/10.1061/JSWBAY.0000796)
- Razzaghmanesh, M. and M. Borst (2019). "Monitoring the performance of urban green infrastructure using a tensiometer approach." Science of the Total Environment. Elsevier BV, 651:2535-2545 (https://doi.org/10.1016/j.scitotenv.2018.10.120).
- Lee, J.G., Borst, M., Brown, R.A., Rossman, L., Simon, M.A. (2015). "Modeling the hydrological processes of a permeable pavement system." J. Hydrol. Eng. 20 (5).
- EPA (Draft)"Reducing Urban Heat Islands: Compendium of Strategies Trees and Vegetation" https://www.epa.gov/sites/default/files/2014-06/documents/treesandvegcompendium.pdf

EPA

References

- Ayers, E. M. and P. Kangas (2018). “Soil Layer Development and Biota in Bioretention” Water, Volume 10, 1587; doi:10.3390/w10111587
- Brown, R. A., and Hunt, W. F. (2012). “Improving bioretention/biofiltration performance with restorative maintenance.” Water Sci. Technol., 65(2), 361–367.
- NJDEP (2007). “Bioretention systems.” Chapter 9.1, New Jersey stormwater best management practices manual, Trenton, NJ, 9.1-1–9.1-10.
- NJDEP (2021). “Chapter 9.7 Small-Scale Bioretention Systems.” New Jersey Stormwater Best Management Practices Manual, NJDEP, Trenton, N.J.
- Tu, M., J. S. Caplan, S. W. Eisenman and B. M. Wadzuk (2020). “When Green Infrastructure Turns Grey: Plant Water Stress as a Consequence of Overdesign in a Tree Trench System” Water, 12, 573; doi:10.3390/w12020573.
- USDA (1991). “Plant Fact Sheet: Indiangrass, Sorghastrum nutans L.” Edited: 05Feb2002, (https://plants.usda.gov/factsheet/pdf/fs_sonu2.pdf) (8/24/2018).
- USDA (2006). “Plant Guide: Bitter Panicum, Panicum amarum Ell.” Edited: 30Jan06 (https://plants.usda.gov/plantguide/pdf/pg_paam2.pdf) (8/24/2018).

Questions?

Acknowledgements

PARS Environmental Inc. performed the first plant survey in December 2012. Nicholas Lund from Montclair University performed the Spring/Summer 2018 plant survey while Nicole Porco of Fordham University collected and analyzed samples for LOI for bioinfiltration units 1-3 as part of their volunteer summer internships. Internships were in partnership with USEPA Region 2. PARS Environmental Inc. collected and analyzed all other soil samples for LOI and performed phophorous extractions. USEPA Region 2 Laboratory performed analysis for phosphorous on extractions from soil samples.

Disclaimer

The USEPA, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's peer and administrative review and has been approved for external publication. Any opinions expressed in this paper are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.