Engineering, Structures and Innovation

Anthony Witcher

Section Editor

Modifying Green Roof Substrates for Nutrient Retention in Urban Farming Systems

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Index Words nitrogen, phosphorus, mushroom, yard waste, compost, aluminum oxide, biochar

Significance to Industry Unused roofs represent up to 32% of the area in urban centers (7). Traditional green roof technology has been steadily transforming urban rooftops into environmental stormwater control systems, which are being rapidly being adopted in many cities around the world. (2,5,6). Parallel to this investment in green infrastructure, urban residents have also developed a desire for more local, sustainable and nutritious food which has fostered the development of urban agriculture projects cultivating local, organically-grown produce (7). Despite a number of review papers on green roof systems (1), few quantitative data exist on the impacts of food crop production practices on the ability of a modified green roof to retain stormwater and any consequent impacts on runoff water quality. Agricultural rooftop farms typically modify green roof substrates with additional organic matter to enhance water and nutrient retention, and crops are also fertilized and irrigated during the growing season, possibly contributing to nutrient runoff issues if not carefully managed.

Urban farmers using vacant lots also face similar issues to commercial rooftop farms, as they typically cannot grow in native urban soils which are generally infertile and are often contaminated with rubble and pollutants such as heavy metals like lead. Raised beds, using sustainable organic substrates with composted material additions are typically used. Correct substrate formulation and nutrient management practices, timely irrigations (even if hand-watered) and the leaching of nutrients from raised beds with rainfall, are common issues facing urban farmers of all backgrounds.

Nature of Work

Background of Novel Amendments One of the principle elements of this study will be to reduce the concentration of phosphorous (total P and dissolved P) from green roof leachates while still providing enough soluble phosphorous in the soil solution to sustain plant growth. Alumina (aluminum oxide) is a by-product of the aluminum smelting industry with a chemical formula Al_2O_3. There have been several horticultural applications of alumina in container and nursery plant studies. Alumina that had been fully saturated with phosphorous (alumina and aluminum phosphate complex) has been applied to woody and flowering herbaceous plants in containers when first potted in commercial grower settings, with plants exhibiting fewer symptoms of phosphorous deficiencies later in production than plants that were given a single dose of Osmocote at planting (4, 8). The current study is also testing the efficacy of addition of biochar in combination with compost to increase cation exchange capacity (CEC), thereby reducing ammonium nitrogen ($NH4^+$) leaching from substrates. Biochar has been shown to increase soil surface area thereby increasing CEC in a similar fashion to fine clay particles which are typically lacking in green roof substrates (3).

This research will be a starting point for understanding substrate amendments and their nutrient retention capabilities for use in both rooftop farming operations and raised-bed urban production at grade. Documenting and communicating this information for urban farmers will help protect water bodies in urban areas, and help formulate better substrate and nutrient management practices for their operations.

Methods This study is divided into two distinct research phases (Phase 1 and Phase 2). Phase 1 consists of small-scale column studies designed to rapidly quantify the leached quantities of phosphorus (P) and nitrogen (N) from the different substrates. In Phase 1, a total of 15 substrates were tested that contain various proportions of the mineral aggregate base of M2® Green Roof media (Stancills, Inc., Perryville, MD), SmartLeaf® municipal compost (City of College Park, College Park, MD), mushroom compost (Laurel Valley Soils, Avondale, PA), alumina (Phospholutions LLC, State College, PA) and biochar (Bartlett Tree Experts, Stamford, CT) (Table 1). Each substrate was placed into 6 replicate columns made from plastic 11 cm diameter Buchner funnels with a substrate depth of 14.6 cm. Each column received 20 cm of distilled water in 2.5 cm aliquots applied every 20 minutes to simulate sequential rainfall events. The columns were allowed to drain and the leachate was collected for every aliquot applied. After the initial 20 cm of simulated rainfall, the columns were fertilized with 100 mL of a 100 mg/L N and 20 mg/L P solution. After 24 hours, an additional 20 cm of simulated rainfall was added in sequential 2.5 cm aliquots, allowing for leaching to be complete between additions. Each column leachate volume was measured, sampled, and analyzed by a commercial lab (AgroLabs, Harrington, DE) for dissolved-phosphorus concentration. Based on the phosphorus retention leaching of the 15 substrates, four were chosen for study in Phase 2 of the study. The substrates that were chose are, from Table 1, substrates 3, 5, 9, and 13 to represent all amendments separately and together within the mushroom composts as mushroom compost demonstrated the most nutrient load. Phase 2 micro-scale studies are being conducted at the University of Maryland Greenhouse complex using sixteen 30-liter plastic tubs (42 cm x 77.5 cm x 14.6 cm) (four replicates per substrate), designed to simulate a green roof installation. These tubs will be filled with 15 cm of substrate and planted with successive vegetable crops over the course of one year. The current planting schedule order is ‘Genovese’ basil (*Ocimum basilicum* ‘Genovese’), ‘Newham’ lettuce (*Lactuca sativa* ‘Newham’), and ‘Lunchbox Red’ peppers (*Capsicum annuum* ‘Lunchbox Red’). After establishing a water retention curve for the substrates, we will use capacitance sensors to automatically activate irrigation valves for each tub, based on a threshold substrate volumetric water content. In addition, a simulated 2.5 cm rainfall event will be applied to each replicate tub; the leachate out of each tub will be collected, measured for volume, and sampled for N and P concentrations. Each tub is equipped with a catchment device that allows the collection and securing of the first flush of each rain event which represents the first 1 mm of rainfall. The remaining 2.4 cm of rainfall is collected in a separate container for each tub. The plants will be measured for overall vigor and yield to rate their performance in each substrate.

Results and Discussion Due to space limitations, only initial P results from Phase I are presented and discussed. In all substrates containing SmartLeaf® or mushroom compost, the total dissolved-P leachate content (volume x concentration, mg) was significantly lower from substrates containing alumina than from substrates without alumina (Figs. 1 and 2). The substrates containing alumina also retained more P after application of fertilizer and the eight 2.5 cm simulated rainfall events. From these preliminary data, there does not appear to be any significant difference in dissolved-P retention when the amount of alumina was increased in the substrate (5% or 10 %), in combination either with the mushroom or SmartLeaf® compost substrates.

In all mixes containing SmartLeaf®and mushroom compost, the amount of leached dissolved-P was not significantly affected either by the presence of biochar or the proportion of biochar in each mix (10% or 20%). There may be an antagonistic effect that biochar has on the alumina-mediated P retention, as substrates with both high biochar and alumina leached more dissolved-P than substrates amended with alumina and lower biochar fractions. However, the purpose of biochar in this experiment was not necessarily to increase P retention, but to increase soil fertility by the effect of improving CEC in soils, and thus retain more N.

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Table 1. Composition of the fifteen substrate formulations tested, expressed as a percent, by volume. M2B Stands for the base M2 green roof media used in all substrates.

Substrate #	Substrate Composition, by Volume
1	100% M2B
2	80% M2B + 20% SmartLeaf Compost
3	80% M2B + 20% Mushroom Compost
4	75% M2B+ 5% Alumina + 20% SmartLeaf
5	75% M2B+ 5% Alumina + 20% Mushroom
6	70% M2B+ 10% Alumina + 20% Smart Leaf
7	70% M2B+ 10% Alumina + 20% Mushroom
8	70% M2B+ 10% Biochar + 20% SmartLeaf
9	70% M2B+ 10% Biochar + 20% Mushroom
10	60% M2B+ 20% Biochar + 20% SmartLeaf
11	60% M2B+ 20% Biochar + 20% Mushroom
12	65% M2B+ 5% Alumina+ 10% Biochar + 20% SmartLeaf
13	65% M2B+ 5% Alumina+ 10% Biochar + 20% Mushroom
14	55% M2B+ 5% Alumina+ 20% Biochar + 20% SmartLeaf
15	55% M2B+ 5% Alumina+ 20% Biochar + 20% Mushroom

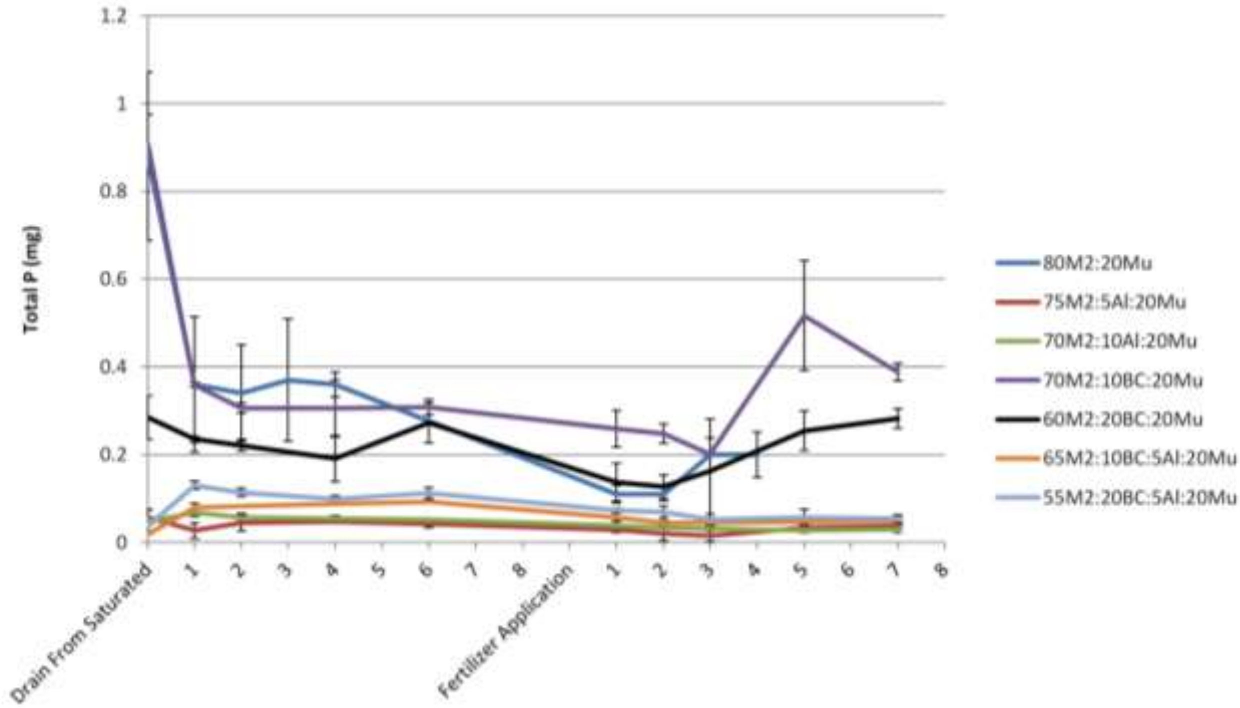

Figure 1. The effects of biochar and alumina on the leaching of dissolved-phosphorus from each substrate containing base green roof media (M2), mushroom compost (Mu), alumina (Al), and/or biochar (BC).

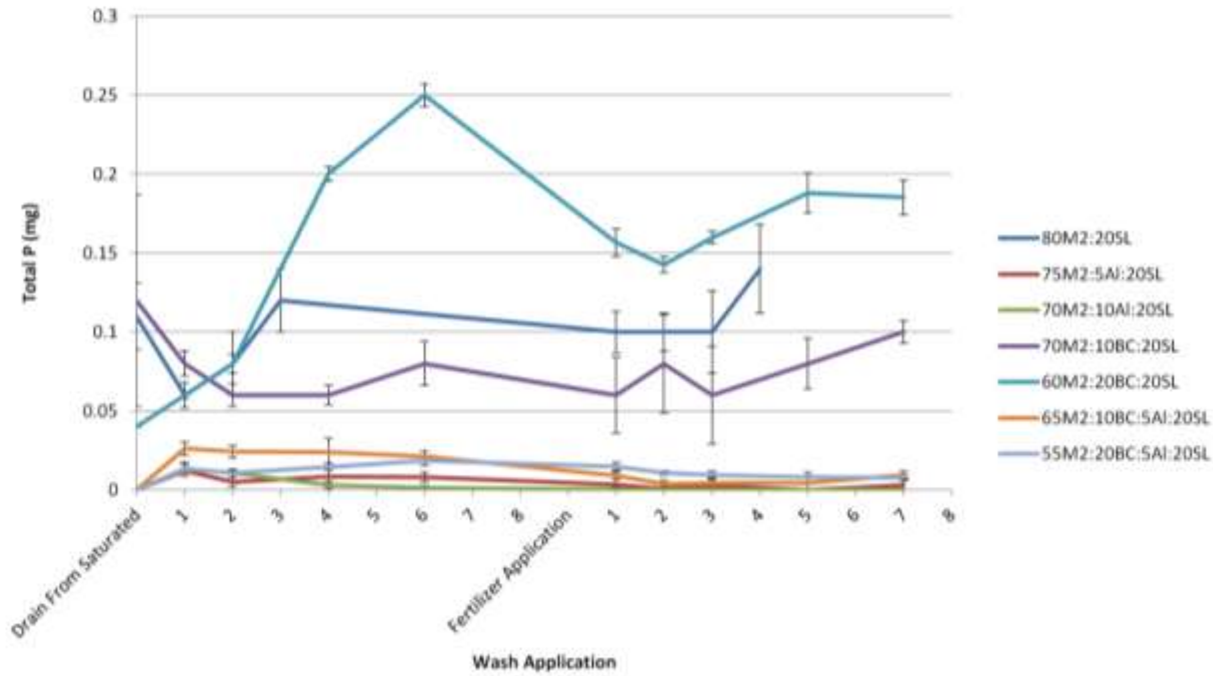

Figure 2. The effects of biochar and alumina on the leaching of dissolved phosphorus from each substrate containing base green roof media (M2), SmartLeaf® compost (SL), mushroom compost (Mu), alumina (Al), and/or biochar (BC).

Monitoring Urban Landscapes to Measure Ecosystem Services

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Significance to the Industry Accurately measuring the daily water use of plants is useful, not only to understand the daily and seasonal water requirements of different species, correlated with age and climatic conditions, but also to assess the capacity of plants to do "work" i.e., provide ecosystems services. In this case, we are interested in determining how much water can be transpired by trees and grasses, to reduce stormwater runoff, provide a monetary value for these benefits and incentivize green infrastructure development in urban areas.

Nature of Work We have been monitoring an urban plaza at the U.S Tax Court in Washington, DC since 2015, to assess the daily and seasonal water use of bald cypress trees (*Taxodium distichum*) and zoysia grass **(***Zoysia japonica*). The tree/grass system is planted in a concrete overpass over the US395 highway that passes underground at that location (Fig. 1). In addition to receiving direct rainfall, the site is irrigated using stormwater runoff collected from the roof and a hardscape portion of the plaza. This runoff is collected in two 13,700 L (3,000 gal) tanks in the basement garage of the building, which are pumped out to irrigate the plaza whenever the tanks contain sufficient water**.**

The primary objective of the study is to provide daily and seasonal water use (evapotranspiration) data for these two plant components at the US Tax Court, over time. Secondly, by providing a daily water balance of water inputs and outputs for this landscape, we can provide annual water budgets which calculate the mitigated cost of potable water for irrigation, as well as the reduction in impervious surface fees for the site.

Half of the plaza's cypress trees (558 m^2 of total surface area; n=10) and approximately 335 m^2 of zoysia grass (n=4) were continuously monitored using a combination of 10HS and GS1 soil moisture sensors (Meter-Group, Inc.; Pullman, WA), flow meters (Badger Meter; Milwaukee, WI) and environmental sensors (see Fig. 2 for sensor layout). Each monitoring point (for both cypress and zoysia) was sensed at 3 cm (1 in.), 15 cm (6 in.) and 30 cm (12 in.) depths in the soil profile. The change in soil moisture (δVWC) at each of these depths is continuously measured and then summed (Σ) between rainfall or irrigation events, to provide an average estimate of daily water loss (K_S, as illustrated in Fig. 3.) from the top 30 cm of the root zone of each species (3, 4). The weather station (Meter-Group, Inc.) at the site provides high-resolution environmental data for total radiation (pyranometer), air temperature and relative humidity (VP4), wind speed and direction (sonic anemometer) and rainfall (ECRN-100). From these variables, the daily reference transpiration (ET_o) was calculated using the FAO56 version of the Penman-Monteith model (1).

Data were logged using EM50R radio dataloggers (Meter-Group, Inc.) on a 5-minute basis, and transmitted to a computer via radio base station on site. Data were then assimilated into an online database and charted graphically using Sensorweb™ software (Mayim, LLC; Pittsburgh, PA). The daily water balance integrates inputs from daily rainfall and irrigation (flow), and outputs using reference evapotranspiration (ETo) and the average Ks values (from cypress and zoysia), to estimate daily water use (ETc, Fig. 4). Real-time data are available to irrigation managers over the internet through a password-protected site; alerts can also be set, e.g. the depth of water in the capture tanks are automatically sent whenever there is more than 1000 L (260 gal) water in the tanks.

Results and Discussion An example water balance for all cypress trees in 2017 is shown in Table 1. Total area covered by cypress in this area of the plaza was 558 m2. Total water inputs from rainfall and irrigation totaled 628,540 L during the year, with over 75% of that total coming from rain. Total estimated evapotranspiration from the cypress trees was 142,521 L, or about 23% of total water supplied. Total rainfall for the site was over 1100 mm (43 in.) in 2017, which exceeded the 30-year average for Washington, DC. Rainfall in May and July was particularly heavy, which contributed to the large imbalance in water supply and use by the trees. Interestingly zoysia, which covered 335 m2 of the site and received a total of 431,663 L of rain and irrigation during 2017 (data not shown), but transpired 87,198 L (about 20% total water). So proportionately, zoysia evapotranspired as much as the cypress trees, probably because the zoysia thatch provided a large surface area for direct evaporation of rainfall and irrigation.

Total estimated water use for cypress and zoysia during 2015, 2016 and 2017 are given in Table 2 and are quite consistent, as all three years were at or above 30-year average rainfall totals with few periods of drought. The stormwater credit trading values are calculated from the average credit price for each year, which can be freely accessed from Department of Energy and Environment's stormwater credit program website (2). Based on what we believe are relatively conservative water use estimates, the ecosystem stormwater services provided by one half of this plaza (0.089 Ha) were $85,635, $102,277 and $122,584 over the three years, averaging over $1.16M / Ha in stormwater services.

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Figure 1. The United States Tax Court Plaza situated over the US395 Highway in Washington, DC.

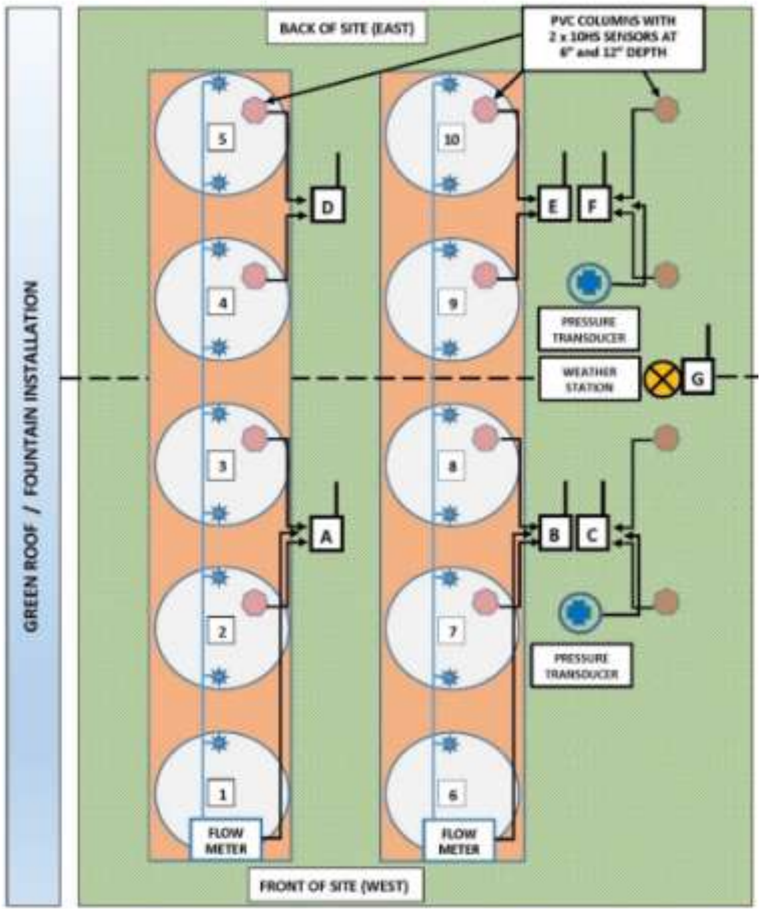

Figure 2. Site Installation diagram of the sensor network: Pink hexagonal icons indicate soil sensor locations in numbered bald cypress trees and four positions within the zoysia grass area. Letters within squares indicate EM50R radio dataloggers. Other sensors noted in annotated boxes.

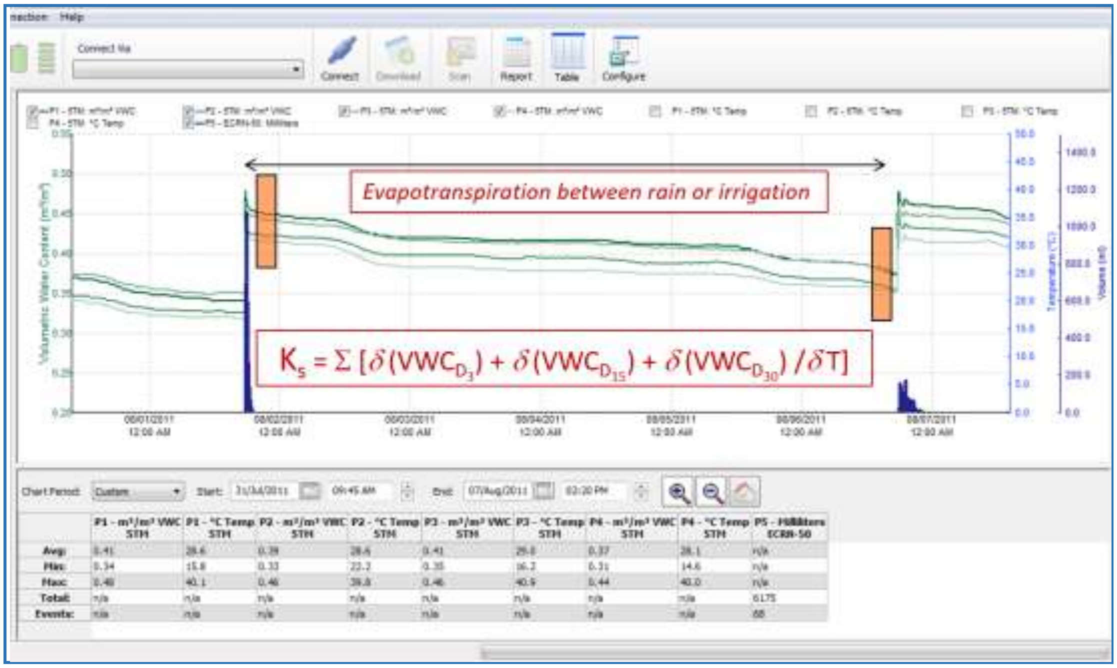

Figure3. Estimating average daily water loss (K_s) values from soil moisture data at three depths (3 cm**,** 15 cm and 30 cm), between rain or irrigation events.

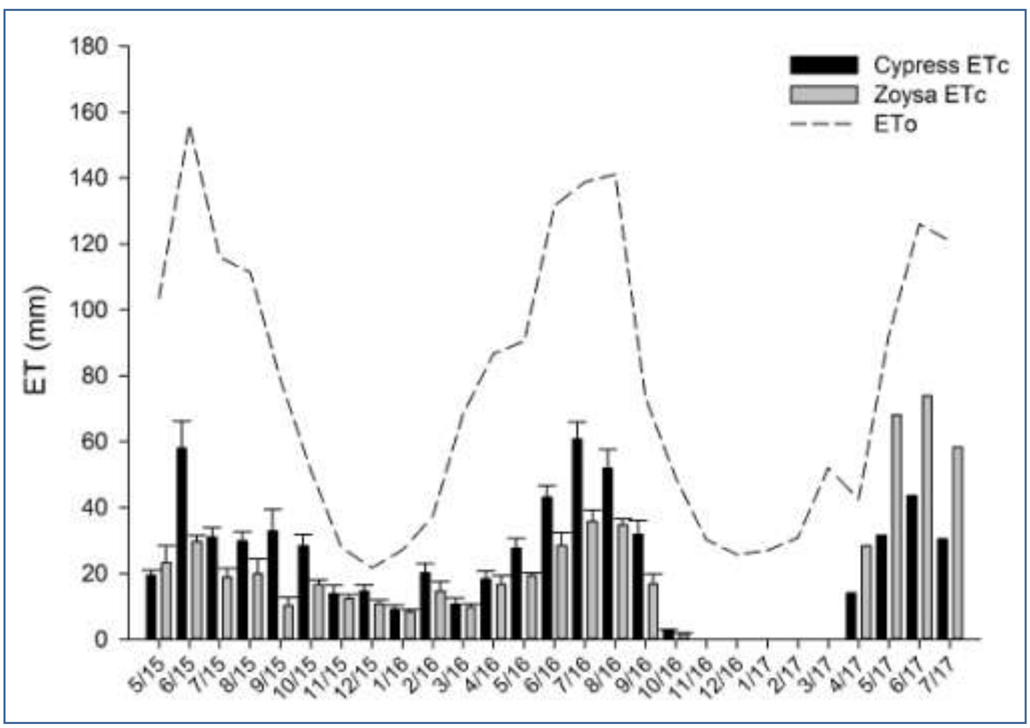

Figure 4. Reference evapotranspiration (ETo), and bald cypress and zoysia grass evapotranspiration (Kc) from May 2015 through July 2017.

Table 1. Monthly water balance for bald cypress trees in 2017, showing precipitation, irrigation and total water inputs, with estimated bald cypress evapotranspiration (ETC), and the resultant balance in liters (L).

Cypress Monthly Summary (2017)					
Month	Prec. (L)	Irrigation (L)	Total Inputs (L)	ETc (L)	Balance (L)
January	42,249	0	42,249	----	----
February	5,012	0	5,012	----	----
March	72,236	0	72,236	----	----
April	13,930	8,254	22,184	7,235	14,949
May	108,468	22,376	130,843	14,910	115,933
June	14,597	19,362	33,959	17,963	15,997
July	141,027	21,378	162,405	24,614	137,791
August	71,684	21,836	93,520	18,622	74,898
September	28,540	26,485	55,025	20,013	35,012
October	39,465	23,612	63,077	18,569	44,508
November	50,391	8,998	59,389	12,710	46,679
December	8,138	0	8,138	7,886	252
Total	476,239	152,301	628,540	142,521	486,019
Remaining water depth in mm					872
Cypress Area = 557.4 m^2					

Table 2. Total evapotranspired water totals for the sensed portion of the US Tax Court, and the potential stormwater credit trading value of that water from 2015 – 2017.

Year	Cypress (L)	Zoysia (L)	Total (Gal)	SW Trading Value (Annual SRC valuation)
2015	127,213	47,438	45,071	$85,635
2016	152,496	61,737	55,285	$102,277
2017	142,521	87,198	60,685	$122,584
Total	422,230	196,373	161,041	$310,496

Evaluation of Shade Cloth Color in Cooling Efficiency

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Index Words Solar radiation, reflective shade, photosynthetic active radiation

Significant to Industry Black, white, and reflective shade materials, each rated at 50% light transmission, were compared to no shade on four identical small Quonset-style cold frames. Results suggest minimal differences in temperature during the hottest time of day using these structures. The white shade initially had higher photosynthetic active radiation (PAR) levels than the reflective or black cloths; however, this advantage slowly diminished over time as the cloth became dirty. The white shade's increase in PAR with similar cooling efficiency to black and reflective might be useful to growers needing more light but also desiring decreased heat. The structures used in these trials would be considered a worst-case scenario for cooling. More modern structures may provide different results. There are many shade cloth types and designs. These trials focused only on standard knit cloth materials.

Nature of Work Shade is used in specialty crop production systems to alleviate stress associated with excess solar radiation and resulting increased air temperatures. Protected agriculture structures are extremely efficient in capturing solar radiation. A standard 30 ft. x 96 ft. greenhouse has the capacity to gain one million BTU's per hour on a sunny day when ventilation is turned off. The rate of heat gain can quickly surpass the rate of heat loss through mechanical or natural ventilation leading to supra-optimal air temperatures for crop production. To reduce the amount of solar radiation entering glazed structures, growers utilize shade compounds, fabrics, and pigmented films. These techniques reduce solar radiation gain; however, they also reduce PAR and other wavelengths important for plant growth and development. Through industry development, shade cloth products have been made available to improve cooling efficiency without the sacrifice of necessary light levels for optimum growth.

Willits and Peet (3) demonstrated an inherent inefficiency of black shade materials due to heat absorption and re-radiation of heat back into the greenhouse. By cooling the black cloth through evaporative cooling, a 55% increase in cooling efficiency was demonstrated. In a later study, Willits (2) further demonstrated that solar energy absorption affected cooling efficiency of the cloth and that shade cloth temperature and floor temperature were correlated. White and reflective shades have been developed and marketed to reduce greenhouse air temperature but little validated research has been published demonstrating this advantage. The purpose of this study was to evaluate commonly used black, white, and reflective knit shade materials for greenhouse cooling efficiency.

Four small Quonset-style cold frames at the Ornamental Horticulture Research Center in Mobile, Alabama were used to compare 50% black, 50% white, and 50% reflective knit-type shade cloth materials to a structure with no shade. Each cold frame measured 8.75 m in length, 5.5 m in width and were 3 m in height at the apex with an east to west orientation. Natural ventilation was accomplished through two large doors on the east and west endwalls, each with 6.5 m^2 vent area that provided a 0.27 vent area to floor area ratio. Each structure was outfitted with temperature and PAR sensors attached to a data logger programmed for 30 minute logging intervals. This study took place in the summer of 2016 and was repeated in the summer of 2017. In 2016, the trial was conducted from August 3 to August 29 and five consecutive days in each replicate (week) were used for analysis. In 2017, the trial was conducted between August 15 and September 13 and seven days in each replicate (week) were used in the analysis.

Each cold frame represented an experimental unit. Replication was accomplished over time with the shade cloth being randomly exchanged among houses each week. The experimental design was a Latin square blocked by replicate (week) and cold frame. Date of the experiment was included as a random variable. Mean comparisons were analyzed for both PAR and temperature for the time of day these variables were at the greatest numerical value across all replicated weeks.

Results and Discussion The mean maximum temperature occurred at 1:30 PM. At 1:30, no differences in temperature were observed among structures covered with black (33.7 °C), reflective (34.0 °C) and white (34.0 °C) shade cloth. The temperature in all cold frames with shade cloth was approximately 4.5% lower than the non-shaded cold frame. During this same trial, the maximum PAR levels occurred at 12:30 PM. All shade materials resulted in different PAR levels at this time, with white shade cloth providing 42.7% and 20.7% more PAR than black and reflective shade cloth, respectively.

During the 2017 trial, the mean maximum temperature also occurred at 1:30 PM. At 1:30, white shade cloth was 1.2 % greater in temperature compared with black and reflective shade cloth. No differences were observed between black and reflective shade cloth in mean temperature at 1:30 PM. In the same trial, the difference in PAR between white and the other two shade treatments was considerably lower than the 2016 trial with white providing 26% and 17% more PAR when compared to black and reflective, respectively.

The increased PAR levels of the white shade over the black and reflective shade cloth is thought to be a result of the semitransparent nature of the white shade cloth material. A third study was conducted in 2018 comparing the same black, white, and reflective cloths but also included an additional proprietary shade material (data not shown). In this trial, maximum daily PAR readings were again compared among the black, white and reflective shad cloths; however, the difference between white shade cloth and the other shade treatments was further reduced when compared to the 2016 and 2017 trials. We believe the gradual reduction in the difference in PAR between the white shade cloth and other shade treatments was due to a buildup of dirt or mold on the white shade cloth.

A separate trial was also conducted on two commercial-sized cold frames at a collaborating nursery where only black and reflective were compared. No differences were observed between the black and reflective shades during the hottest time of the day (data not shown). In all trials, there were few differences observed when comparing black and reflective shade cloths. Further analysis of the rate of temperature gain may result in greater differences between treatments. It is important to understand that all the structures used in these trials were poorly designed for natural ventilation and would be considered worst case scenarios. More modern and taller structures with greater vent to floor area ratios may provide different results. Little peer reviewed comparisons of black and reflective shade cloth were found in the literature; however, industry reports have shown some advantages to reflective clothes (1). The differences in results among our studies and other reports suggest that a “one size fits all” approach in comparing shade types is not appropriate for general comparisons. Many factors should be considered when comparing shade products. A product may work well on one structure but perform less efficiently on a different structure. Factors to consider in comparison should include mechanical versus natural ventilation, vent to floor area ratio, ceiling height, and differences between double and single poly covered structures and plant density.

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Table 1. Comparison of mean greenhouse air temperature (°C) at 1:30 PM for black, white and reflective shade 50% knit shade cloth[ZY].

	Trial[X]	
Shade Type	2016	2017
No Shade	35.6 a[W]	34.5 a
White	33.7 b	32.5 c
Reflective	34.0 b	33.3 b
Black	34.0 b	32.7 b

[Z]Greenhouse structures consisted of 4 quonset style cold frames measuring 5.5 m (width) x 8.75 m (length).

[Y]Average maximum daily temperature occurred at 1:30 PM.

[X]Trials in 2016 and 2017 took place in Aug. 3 to Aug. 29 and Aug. 15 to Sept. 13, respectively.

[W]Means within column followed by the same letter do not significanlty differ.

Table 2. Comparison of mean greenhouse PAR (°C) at 12:30 PM for black, white and reflective shade 50% knit shade cloth[ZY].

	Trial[X]	
Shade Type	2016	2017
No Shade	35.6 a[W]	34.5 a
White	33.7 b	32.5 c
Reflective	34.0 b	33.3 b
Black	34.0 b	32.7 b

[Z]Greenhouse structures consisted of 4 quonset style cold frames measuring 5.5 m (width) x 8.75 m (length).

[Y]Average maximum daily PAR occurred at 12:30 PM.

[X]Trials in 2016 and 2017 took place in Aug. 3 to Aug. 29 and Aug. 15 to Sept. 13, respectively.

[W]Means within column followed by the same letter do not significanlty differ.