SUBSTRATE EVALUATION AND IRRIGATION SCHEDULING

FOR GREEN WALL SYSTEMS

by

JOHANNAH HELEN BIANG

(Under the Direction of David Berle)

ABSTRACT

This experiment was designed to determine a suitable substrate for green wall systems and an irrigation schedule for greatest growth and uniform water distribution. The soilless/compost substrate was found to be the most suitable based on PAW. Basil yield was not different between irrigation treatments, though there was a difference in yield between sides of the walls, with the east side showing a higher yield than the west side. Differences were noted, however, in water use between treatments. Sensor-controlled irrigation treatment was nine times more efficient than the other two treatments, without sacrificing yield. Contour graphs of water distribution showed differences in volumetric water content between the various levels within the walls. As expected, the top level was drier than the middle and bottom of the wall, while the middle and bottom were equally wetter.

INDEX WORDS: green wall, plant available water (PAW), irrigation scheduling, volumetric water content

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DEDICATION

I would like to dedicate this thesis to my family. Without your support and encouragement it would not have been possible. Dad, thanks for always challenging me to work hard and dig deeper than I ever thought possible. Thanks for letting me help you in the garden when I was young, even when I made mistakes. Without those experiences I would not have the love of horticulture that I have today, and would definitely not be writing this dedication. Mom, thanks for always listening, even when I did not make sense, and always rejuvenating my spirit with your amazing cooking. To Jacob, Emily, and Erik, thanks for doing your job, and keeping my mind off the stress that went with this thesis and believing in me when I did not believe in myself. You guys are the best. To my Grandmas, Lorraine and Jean, you both inspired and encouraged my love for horticulture from day one. From the walks in the woods to the seeds from Grandma Erickson's house; you've both done more than you will ever know.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Availability of agricultural land in the U.S. is decreasing while human population continues to increase. By 2030, the U.S. population is projected to increase to 363 million (Census, 2000). In the U.S., the 2010 Census reported 80.7% of the listed population occupying urbanized areas (Census, 2012). From 1982 to 2007, 14 million acres of prime U.S. farmland was lost, mostly due to development, representing an increase of 56% in development during this period (USDA, 2009). In U.S. urban areas, availability of productive land competes with the growing population. At the same time, increasing demands for potable water impose greater constraints on water used for food production. Agriculture currently accounts for 80% of the ground and surface water consumed in the U.S. (USDA-ERS, 2012). More efficient production systems are needed, in terms of space and water required, in order to meet this increasing demand.

Green walls offer a complimentary approach to meet this need. For purposes of this thesis, a green wall is defined as a growing system in which plants are grown in a box or container mounted to the side of a building or built freestanding. Green walls have been used to reduce HVAC needs of buildings in much the same way as green roofs. Green walls decrease surface temperature of buildings which can result in decreased energy consumption (Wong et al., 2010) and consequently decreasing the urban heat

island effect (Bass et al., 2003). In addition, Wong et al. (2010) also found that green walls reduce the ambient outdoor temperature, which can also lead to a decrease in the urban heat island effect. Other potential environmental benefits of green walls include decreasing storm water runoff, increasing biodiversity, decreasing noise pollution, increasing health and wellness, and protecting building infrastructure (Weinmaster, 2009). In some instances, green walls have been incorporated into the design of larger buildings for purely aesthetic reasons. Green walls allow for maximum production with minimum footprint, and in many situations, allow plants to thrive in sites not traditionally hospitable to growth. When used to grow edible plants, green walls have the potential to increase food production in urban areas as well as in structures such as high tunnels and greenhouses, further increasing yield per square foot.

Virtually all research on green walls has focused on ornamental applications, though use of green walls for food production is frequently discussed in popular articles and promoted through purveyors of do-it-yourself gardening information. An article in CNN Money highlights a restaurant entrepreneur who built a green wall on the side of his building and is marketing locally grown ingredients (Zimmerman, 2010). Grower Talks, a leading horticultural trade publication, also highlights the idea of vertical gardening in an article encouraging growers to produce vegetable transplants for these types of systems (White, 2012).

Without a basic understanding of substrates and irrigation, advanced research on food crop production using green walls cannot be conducted. Several vendors offer versions of prefabricated green wall systems, from hanging “pockets” to commercial wall covering systems. However, the green wall designs for commercial application rely on

technology and production systems primarily developed for green roofs. Although some research has focused on the environmental benefits of green walls, there has been little research on the fundamental design of the system, specifically with respect to substrates, irrigation design, and irrigation scheduling.

Research on green roof systems and container production, being closest in growing conditions, can provide guidance in pursuing green wall research. Similarities consist of the use of soilless substrates and drip irrigation, limited growing space, weight restrictions, and water management. Though similar, green walls present a unique set of growing conditions. With green walls, the substrate profile is much deeper than that of green roofs or containers, making water distribution throughout the entire profile a potential issue. This suggests, that for green wall systems, substrates should be evaluated based on water holding capacity and irrigation design should focus on evenly distributing water throughout the substrate profile. With green walls, there is also the issue of potential water distribution affected by gravity, creating an extremely wet region at the bottom, while leaving the top dry. Green roofs differ in that their substrate profile is shallow to minimize the weight applied to the roof. Containers production is similar to green roofs in that their planting depth is also limited.

Substrates for green roof systems are often compared by evaluating physical and chemical characteristics, as well as their water-holding capacity. Panayiotis et al. (2003) evaluated lightweight amendments, focusing on overall substrate weight, based on their weight at saturation and at field capacity as well as their physical characteristics, such as bulk density and porosity, and chemical characteristics, like EC and pH. They found that, even though the mixture of peat/urea formaldehyde resin foam was lighter

than the sandy loam/urea formaldehyde resin foam mixture and the sandy loam/peat/perlite mixture, yields were not the greatest due to water logging and increased EC levels (Panayiotis et al., 2003). Plant growth was greatest in the mixture of sandy loam/urea formaldehyde resin foam even though it was slightly heavier (Panayiotis et al., 2003).

In a study conducted by Kotsiris et al. (2012), substrate type (lightweight) and depth were evaluated with respect to plant growth. In their study, substrate chemical and physical characteristics were also evaluated to determine compliance with green roof guidelines established by Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL) (FLL, 2008). Three locally obtained substrates were evaluated: 1) pumice/peat/perlite; 2) pumice/compost/zeolite; 3) sandy loam soil/perlite/zeolite, at two depths. All substrates were in compliance with FLL guidelines. Plant growth was more affected by depth than type, with greater growth in the deeper substrate (Kotsiris et al., 2012).

In addition, Nektarios et al. (2011) conducted a similar study, evaluating substrate type and depth with respect to plant growth in drought conditions by comparing chemical and physical characteristics of the substrate as well as physiological indicators of the plants grown. Two substrates were evaluated, one containing soil and one soilless, with two planting depths and two irrigation regimes during drought stress. Results indicated that substrate depth was the most influential factor in plant growth, with the deeper substrate resulting in better plant growth.

Green roof studies often focus on substrate weight, and thus more emphasis on physical characteristics. For green wall systems, weight is a concern, but the primary

focus is on water movement and distribution throughout the wall and therefore substrate water-holding capacity is of major importance. For any situation, selecting a substrate that holds water, but not so tightly that the plants cannot access it, is crucial. In green roof studies evaluating substrates, Nektarios et al. (2011), Kotsiris et al. (2012), Panayiotis et al. (2003) relied on moisture release curves (MRCs) to determine the water holding capacity of the substrates. However, O'Meara (2012) states that MRCs are an inaccurate method of determining how much water is actually available to plants. Typically, to determine plant available water (PAW) using MRCs, water content is measured over a series of pressures applied to the soil in a pressure plate. However, the hydraulic conductance of soilless substrates at low water content is so low that this type of equipment is unable to completely extract the water ((Van Iersel, 2012) unpublished results).

Additionally, MRCs use permanent wilting point to determine PAW. The permanent wilting point is commonly defined as the water content of a soil/substrate at a matric potential of -1.5 MPa. However, its been found to depend on species, soil type, and climate (Tolk, 2003, Taiz and Zeiger, 2002), and its use has therefore been questioned (Tolk, 2003). Thus, a simpler, more reliable method to determine PAW in soilless substrates, which utilizes actual plants in the substrates to be evaluated, can be used.

To determine PAW, the substrate weight when saturated with water is compared to the substrate weight when plants have taken up all available water, at plant death. Using plant death rather than wilting point to determine PAW gives growers a simpler point to determine. Additionally, O'Meara (2012) found that there is minimal water loss

after wilting point. Similarly, to determine plant unavailable water, the substrate weight when plants have taken up all available water is compared to the substrate weight when oven-dry. Using these methods to determine PAW and plant unavailable water is an effective method to determine the ability of the substrate to hold water, and more importantly, to make that water available to the plant (O'Meara, 2012).

In green roofs, irrigation systems are typically designed to establish new plantings and used minimally thereafter. VanWoert et al. (2005) evaluated watering regimes in a green roof study to determine the minimum irrigation requirements for plant survival and maintenance. Additionally, green walls are used to retain storm water; further exemplifying their minimum irrigation needs, and are not centered on quick plant growth, as in a green wall system producing food. In a system where minimal irrigation is required and quick plant growth is not a main goal, irrigation scheduling is less important than in green walls systems, where the substrate profile is deeper and evenly distributing the water throughout the profile is more challenging. Water movement is the biggest factor in determining an irrigation schedule for green wall systems. Based on systems currently on the market, walls are irrigated by drip irrigation on the top and water is allowed to move through the system via gravity. This creates a problem of water saturation at the bottom of the wall, leaving the top dry and the middle somewhere in between. Therefore, an irrigation schedule that promotes more evenly distributed water throughout the wall with minimum runoff is desired.

To design an efficient greenhouse irrigation system and schedule, Nemali and van Iersel (2006) incorporated soil moisture sensors and dataloggers into a solenoid controlled system to measure the volumetric water content (VWC) of the substrate to

determine precisely when a plant should be watered. By using a datalogger to control the system they were able to measure VWC as well as control the irrigation amount based on various VWC set points. When the substrate moisture content fell below the VWC set point, the irrigation system was activated and irrigated for a set amount of time. This allowed for precision irrigation, based on sensor-controlled irrigation, using specific set points to signal an irrigation event (Nemali and van Iersel, 2006). This type of controlled system can be applied to the irrigation of green walls, incorporating an automated irrigation system, using a specific set point as designed by Nemali and van Iersel (2006).

While using dataloggers and set points to indicate precisely when a plant should be watered is ideal, many green wall contractors and designers do not have access to this type of equipment. An alternative method of scheduling irrigation for a green wall system is using predicted daily evapotranspiration (ET) rates to predetermine the rate and timing of irrigation. Predicted ET rates can be determined by gathering past daily ET data from a weather station website and taking an average for a period of time. This averaged rate provides an estimate of how much water will be lost. By calculating the surface area planted, and then multiplying it by the predicted averaged ET rate for a specific period of time, a total volume of water is calculated that would need to be applied daily to the system to account for ET.

Research Objectives

Without pertinent and specific research on substrate selection and irrigation scheduling, advanced research on vegetable production in green walls cannot proceed.

This study was designed to provide a foundation for future research. The objectives of this study were to:

1) determine appropriate substrate for green wall system based on PAW;

2) identify an efficient irrigation schedule, which promotes uniform water distribution; and

3) use sensor data to model water distribution throughout the walls

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CHAPTER 2

SUBSTRATE EVALUATION AND IRRIGATION SCHEDULING FOR GREEN WALL SYSTEMS[1]

[1] Biang, J.H., D.C. Berle, and M.W. van Iersel. To be submitted to *HortTechnology*.

Abstract

This experiment was designed to determine a suitable substrate for green wall systems and an irrigation schedule for greatest growth and uniform water distribution. The soilless/compost substrate was found to be the most suitable based on PAW. Basil yield was not different between irrigation treatments, though there was a difference in yield between sides of the walls, with the east side showing a higher yield than the west side. Differences were noted, however, in water use between treatments. Sensor-controlled irrigation treatment was nine times more efficient than the other two treatments, without sacrificing yield. Contour graphs of water distribution showed differences in volumetric water content between the various levels within the walls. As expected, the top level was drier than the middle and bottom of the wall, while the middle and bottom were equally wetter.

Introduction

Little research has focused on the fundamental design of green walls systems, specifically with respect to substrates, irrigation design, and irrigation scheduling. Wong et al. (2010) found that green walls decrease the surface temperature of buildings, which can result in decreased energy consumption, and reduce the ambient outdoor temperature, both consequently decreasing the urban heat island effect (Bass et al., 2003). Ornamental plants are often grown in green walls; however, incorporating edible plants is a viable option for producing food in urban areas where horizontal space is a limited resource, and in temperature-controlled environments such as greenhouses and high tunnels.

Given the dearth of research on green walls, research on green roof systems and container production, being closest in growing conditions, can provide guidance in pursuing green wall research. Similarities consist of the use of soilless substrates and drip irrigation, limited growing space, weight restrictions, and water management. Though similar, green walls present a unique set of growing conditions. Green roof substrates are often evaluated based on their chemical and physical characteristics (Kotsiris et al., 2012, Nektarios et al., 2011, Panayiotis et al., 2003) with respect to substrate weight. Concerns are similar in green wall systems; however, there is an additional concern for water movement and distribution throughout the wall, given that the substrate profile is much deeper, and therefore substrate water-holding capacity is an important factor.

In green roof studies evaluating substrate water-holding capacity, moisture release curves (MRCs) are often used. However, O'Meara (2012) states that MRCs are an inaccurate method of determining how much water is actually available to plants. Typically, to determine plant available water (PAW) using MRCs, water content is measured over a series of pressures applied to the soil in a pressure plate. However, the hydraulic conductance of soilless substrates at low water content is so low that this type of equipment is unable to completely extract the water ((Van Iersel, 2012) unpublished results).

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To determine PAW, the substrate weight when saturated with water is compared to the substrate weight when plants have taken up all available water, at plant death. Using plant death rather than wilting point to determine PAW gives growers a simpler point to determine. Additionally, O'Meara (2012) found that there is minimal water loss after wilting point. Similarly, to determine plant unavailable water, the substrate weight when plants have taken up all available water is compared to the substrate weight when oven-dry. Using these methods to determine PAW and plant unavailable water is an effective method to determine the ability of the substrate to hold water, and more importantly, to make that water available to the plant (O'Meara, 2012).

Current irrigation scheduling techniques developed for container production by Nemali and van Iersel (2006), utilizing soil moisture sensors and dataloggers into a solenoid controlled system, can be utilized to design and ultimately identify an irrigation system that will evenly distribute water throughout the green wall system. Since this type of system may not be accessible to green wall contractors and designers, an alternative irrigation method will also be evaluated using predicted evapotranspiration (ET) rates to predetermine the rate and timing of irrigation.

The objectives of this study are 1) determine an appropriate substrate for green wall systems based on PAW; 2) identify an efficient irrigation schedule, which promotes uniform water distribution; and 3) use sensor data to model water distribution throughout the walls.

Materials and Methods

Substrate Evaluation

Three substrates were evaluated to determine the most suitable for use in the green wall system, based on PAW. The three substrates were selected based on previous studies on green roofs, professional opinion, and ease of access (Nektarios et al., 2011, Kotsiris et al., 2012, Rowe et al., 2006, Higgins). All substrates contained organic matter, as most substrates used in green roof research also contain organic matter (Rowe et al., 2006). Since green wall systems require lightweight materials and support plant growth in much the same manner as green roofs, a specially developed green roof substrate was one of the substrates evaluated. The green roof substrate evaluated (ItSaul Natural Intensive Garden Roof Media, ItSaul Natural, Alpharetta, GA) consisted of a specially prepared substrate containing 55% PermaTill, 30% coarse river sand, and 15% worm castings compost. PermaTill is an expanded slate material commonly used in green roof systems and is known to have well-draining characteristics (Rowe et al., 2006).

The soilless substrate evaluated was a common soilless substrate (Jolly Gardener Pro-Line Custom Growing Mix, Oldcastle Lawn & Garden, Atlanta, GA), comprised mostly of processed pine bark fines and Canadian sphagnum peat. A common soilless substrate was selected based on information from green wall manufacturers who often recommend soilless substrate in their system designs (Anonymous, 2012). The final substrate evaluated consisted of a 50:50 mix of the same soilless substrate and locally available compost. Compost can be a locally available source of organic matter since many municipalities and farms have active composting programs.

To evaluate the three substrates, a container study was conducted in a controlled greenhouse environment based on the assumption that the PAW response in a container is similar to that in a green wall. *Beta vulgaris* subsp. *Cicla* (Swiss Chard) var. 'Fordhook Giant' was chosen for its adaptability to warmer temperatures and rapid growth habit, making it ideal for expediting the soil-drying process in determining the PAW of each substrate. Swiss chard was started from seed and transplants were grown in a soilless substrate (Fafard 3B, Conrad Fafard Inc., Agawam, MA). The Jolly Gardener soilless substrate was not used at this stage to minimize potential effects on the other two substrate treatments. Transplants were fertilized once a week with water-soluble fertilizer (Jack's Professional Water Soluble Fertilizer 20-10-20 Peat-Lite, J. R. Peters, Inc., Allentown, PA) at 200ppm N after first set of true leaves. Once fully rooted, transplants were planted into one-gallon containers filled with one of the three substrates. Constant liquid feed, using the same fertilizer and concentration, was continued weekly until the chard was fully rooted. Containers were arranged in a complete randomized design with nine replicates of each of the three treatments. During the study, the exposed surface of the containers was covered with aluminum foil to minimize water loss from the soil surface through evaporation.

Containers were watered thoroughly and left in catch pans filled with water for 24 hours. Excess water drained from the containers for one hour. At this point, the containers were considered to be at container capacity (saturation) and the combined weight of the container, plant and substrate was recorded. From this point forward, containers were not watered, allowing plants to extract all available water from the substrates. The study concluded when the plants were dead. Container weights were

recorded at the time of plant death (dead plant weight). The difference in weights between container capacity and dead plant weight represents the amount of water each plant could extract from its substrate, or PAW. Substrates from each container were oven-dried and weighed again. The difference between oven-dried weight and dead plant weight represented the amount of water the plant was unable to extract, or plant unavailable water. The water holding capacity was determined for each substrate by subtracting oven-dried weight from the weight at container capacity. PAW, plant unavailable water, and water holding capacity were also converted to VWC (m^3/m^3) by dividing the differences by container volume.

Bulk density (g/cm^3) was determined for each substrate by subtracting the container weight from the weight at plant death and dividing the difference by the container volume.

Irrigation Scheduling

To evaluate irrigation scheduling methods, a low-cost green wall system was designed and constructed based on commercial models on the market. Walls were built using 44" W x 48" H x 8" D animal fence panels (4 gauge wire, 4" square openings) (Feedlot panel, sheep/goat, Tractor Supply, Athens, GA). Panels were cut and fastened together to form a rectangular freestanding wall (Figure 1). A panel cut from small gauge welded wire fencing (Hardware cloth, Tractor Supply, Athens, Georgia) was added to the bottom panel to increase structural integrity. Industrial strength felt (Green Guard Underlayment, Anjon Manufacturing Industrial, O'Fallon, MO) lined the wire frame to

hold the substrate in place. Stands for the wire frame walls were constructed of wood to keep the green walls above ground.

The soilless/compost substrate was used to fill the walls, based on the results of the substrate evaluation study. The walls were installed in two rows angled on a north-south orientation, with one long side facing east (front) and the other long side facing west (back). This orientation was chosen to assure that both sides of the walls received direct sunlight part of the day. The experimental design included nine walls, with 3 replications of each irrigation treatment in a complete randomized design. These walls were in a high tunnel to eliminate rainfall affects and serve as an example of the use of green walls in a high tunnel production system.

A drip irrigation system similar to that used in commercial green wall systems was installed in each wall. The system consisted of a 1" PVC main line with ¾" vertical PVC pipe going to the top of each wall. At each wall, a flow meter and solenoid valve was installed to monitor and control water flow. A ½" polyethylene tube was attached at the end of the ¾" PVC riser, and run across the top of the wall. Four drip emitters (4L/H, Netafim USA, Fresno, CA) were installed 12" apart in the polyethylene tube with the first and last being 6" from either side of the wall. These emitters were calibrated by placing them over a bucket and measuring the amount of water that was emitted over one hour. This was replicated three times with the resulting flow rate of 3.95 L/H rather than 4L/H.

For each irrigation scheduling treatment, nine soil moisture sensors (10HS, Decagon Devices, Inc., Pullman, WA) were placed in each wall in a grid; three each in the top, middle, and bottom of the wall. A total of 81 sensors were connected to two multiplexers (AM25T, Campbell Scientific, Inc., Logan, UT), which were both connected

to one datalogger (CR10, Campbell Scientific Inc., Logan, UT). Each solenoid valve was connected to a relay driver (SDM-CD16AC, Campbell Scientific Inc., Logan, UT) wired to the datalogger, a system similar to that developed by Nemali and van Iersel (2006). Irrigation control occurred when the solenoid valves opened and closed, depending on treatment, via the relay driver. Voltage output from the soil moisture sensors were recorded every 20 minutes and then averaged every hour. Using a substrate-specific calibration equation (Nemali et al., 2007), the datalogger converted the voltage readings to VWC (m^3/m^3). The calibration equation for the soilless/compost substrate was VWC = (0.954 x voltage) – 0.415.

Three irrigation schedules were evaluated. The first, a sensor-controlled irrigation treatment, used a predetermined set point VWC reading (Kim et al., 2011, Van Iersel et al., 2010, Nemali and van Iersel, 2006). Sensor readings from the middle layer in the wall were averaged and when this average fell below the set point (0.38 $m^3 \cdot m^{-3}$), the wall was watered for 20 minutes, applying 5.27 L of water. The set point and time interval were determined by thoroughly irrigating the walls, allowing them to drain, and recording the time it took for the overall water content to increase by 0.02 $m^3 \cdot m^{-3}$ and the water content at that time (Nemali and van Iersel, 2006).

Two additional, less technologically geared treatments were evaluated. Both were based on plant ET rates that could easily be used with conventional irrigation controllers. The second irrigation scheduling treatment (one-time ET) used the predicted ET rate, applied in one daily irrigation event. The third treatment (multiple time ET), used the same method and volume of water, but split irrigation into three events. This type of irrigation scheduling is based on the concept of irrigating frequently throughout the day,

for a smaller amount of time, to evenly distribute water to the plants as well as reduce the amount of leaching by excess runoff (Tyler, 1996). Presumably this technique would more evenly distribute water throughout the wall system and additionally result in less leaching of the nutrients.

The average ET rate for the study period was determined using past ET data (2011) from the UGA Weather Station in Watkinsville, GA for the period of time the study was conducted. These daily rates were then averaged into one ET rate for the entire period. By multiplying this rate by the wall surface area, the daily ET was determined to be 14.9 L/day. Dividing this volume by the flow rate of 15.8 L/h provided the amount of time [1 hour (60 minutes)] to program the datalogger to water each treatment. This amount of time was rounded to 1 hour (60 minutes) rather than the calculated 0.94 hour (56.5 minutes). For the one-time ET rate treatment the walls were irrigated for 60 minutes each day at 8:00 AM. The multiple time ET rate treatment split the 60 minutes into three irrigation events of 20 minutes each at 6:00 AM, 12:00 PM, and 6:00 PM.

Ocimum basilicum 'Aroma 2' (basil) was chosen based on weather conditions during the study, its quick growth habit, and its adaptability to adverse growing conditions, to evaluate the three irrigation treatments. Transplants were started from seed and fertilized as the chard transplants in the substrate evaluation study. The basil was planted into the east and west sides of each wall by cutting slits in the fabric and inserting the transplants. Transplants were spaced approximately 18" apart in four levels on the wall (top, mid 1, mid 2, and bottom). The top level contained three plants; mid 1 two plants; mid 2 three plants; and bottom two plants. One week after planting, each

transplant was fertilized with ½ fl. oz. solution of the same water-soluble fertilizer as used in the substrate study, mixed at a rate of 1 tbl/gal, using a funnel positioned above each transplant.

The basil was harvested from each wall and weighed. Front (east) and back (west) plants were harvested and weighed separately. Fresh basil weight for each wall was recorded immediately following harvest to minimize differences in weight due to water loss. Samples were then dried in an oven at 70-80 ^{o}C for three days and weighed again to determine basil dry weights. Three separate harvests were made, each at two week intervals, with the first beginning two weeks after planting. For Harvest 1, plants were cut back to the third node. For Harvests 2 and 3, plants were cut back to the fourth and fifth nodes, respectively. Plants were fertilized after each harvest as previously described when basil was transplanted.

Initially, the intention was to harvest and weigh plants only according to irrigation treatment and side of wall, but before Harvest 3, visual observations indicated growth differences among the levels on the wall. For Harvest 3, plants from each of the four levels were harvested and weighed separately. Because each level did not contain the same number of plants, an average weight was calculated for each level by taking the total weight for that level and dividing it by the number of plants in that level.

Flow meter readings recorded the amount of water used by each wall throughout the study. At the end of the study, total water use was calculated for each wall using flow meter data from the planting date to the end of Harvest 3. In addition to calculating total water use, the water use efficiency of each wall was calculated by dividing the total harvested basil fresh weight by the total amount of water used for each wall.

Electric conductivity (EC) of the pore water in the substrate was measured after Harvest 3 to determine the presence and location of nutrients in the wall systems. Measurements were taken at each level within the wall (top, mid 1, mid 2, and bottom). Since EC can be spatially variable, several measurements were taken per level and an average calculated for each level. The number of measurements taken per level was based on the number of plants for that level as indicated in the planting description above. A handheld sensor (WET-2 Sensor, Delta-T Devices, Cambridge, United Kingdom) was used to measure pore electric conductivity (ECp) or the EC of the water available to the plant.

VWC sensor data collected from the datalogger was selected for a sunny day (August 16) as well as a cloudy day (August 19) during the study when basil growth was at its peak, just prior to Harvest 2, based on rainfall and temperature data obtained from the UGA Weather Station in Watkinsville, GA. The sensor data was averaged for the entire day for each of the nine sensors and then averaged between the three green wall repetitions of each treatment to obtain a single value for each sensor location within the wall. These data were then used to generate contour graphs (SigmaPlot 12.3, Systat Software Inc., San Jose, CA) to compare irrigation treatments as well as the different locations within the wall.

Statistical Analysis

For the substrate study and irrigation study, PAW, plant unavailable water, water holding capacity, bulk density, total water use, and water use efficiency were analyzed

statistically using one-way ANOVA. Mean separation was determined using Tukey's Test.

Weights (fresh and dry) from each harvest were analyzed as a completely randomized design with a split plot (east vs. west side) with a general linear model. Harvest 1 and 2 used the same model; however, for Harvest 3, an extra variable was added to account for possible differences in levels (split-split plot). Pore EC was analyzed using the same method as Harvest 3. Mean separation for all data using a general linear model was determined using a pairwise t-test (SAS 9.2, SAS Institute Inc., Cary, NC).

Results and Discussion

Substrate Evaluation

Type of substrate affected PAW, with the green roof substrate having less PAW than both the soilless substrate and the soilless/compost substrate (Table 1). However, there was no significant difference in PAW between the soilless substrate and the soilless/compost substrate (Table 1).

The green roof substrate had a lower water holding capacity than the soilless and soilless/compost substrates (Table 1). The soilless and soilless/compost substrates were not significantly different (Table 1).

Additionally, the green roof substrate had less plant unavailable water than the soilless and soilless/compost substrates while the soilless and soilless/compost substrates were not significantly different with respect to plant unavailable water as shown in (Table 1).

The green roof substrate had a significantly greater bulk density than both the soilless substrate and the soilless/compost substrate (Table 2). Additionally, the soilless/compost substrate also had a significantly greater bulk density than the soilless substrate, with the soilless substrate containing the lowest bulk density (Table 2).

Based on the results above, the soilless/compost substrate was selected for the irrigation scheduling part of this study because: 1) there was no difference in PAW between the soilless substrate and the soilless/compost substrate; 2) compost is a locally produced product that is typically cheaper than soilless substrates; and 3) the soilless and soilless/compost substrates weighed significantly less and a had a lower bulk density than the green roof substrate, which are necessary traits in a green wall system.

Irrigation Scheduling

Since basil is marketed fresh, and yield results were similar for fresh and dry weights, only fresh harvest weights were reported. There was no significant difference in overall harvested basil weight among the three irrigation treatments for any of the harvests (Table 3). One possible explanation for this could be the hardiness of basil and tolerance to excessive moisture in hydroponic conditions (Succop, 1998). Similar results may not have been found had a more moisture sensitive crop been used. There was, however, a yield difference between the sides of the wall harvested for Harvests 1 and 2 (Table 3), with the east side yielding more basil than the west, regardless of irrigation treatment (Table 3).

Similar results were found for Harvest 3 (Table 3); however, in this case, there was an interaction between the sides and vertical levels within the wall system (Table 4).

When yield was separated by wall level for Harvest 3, the bottom level of the walls had the lowest yields regardless of wall side (Table 4). On the east side, the level mid 1 produced the highest yield of basil, while on the west side, the level top and mid 2 produced the highest yield (Table 4). Additionally the east side had greater yields than the west side at all levels (Table 4). These results are consistent with those found in Harvest 1 and 2.

Initially, the walls were oriented on a north-south axis to maximize the amount of light the planted sides would receive. However, a large stand of trees on the west side of the experiment area may have affected yields on the west-facing wall. Light levels on the east and west side were not recorded; but, in a study conducted by Beaman et al. (2009) looking at the edible biomass production of basil at varying irradiance levels, basil produced a greater edible biomass at a higher level of irradiance than at the lower irradiance levels. This may explain the basil yield differences between the east and west wall sides.

Despite the lack of differences in yield, there were significant differences in water applied among irrigation treatments. The sensor-controlled treatment applied less water than both ET treatments (Table 5). There was no difference between the ET rate treatments. This was expected, since both ET rate treatments applied the same amount of water, and the sensor-controlled treatment applied water only when the VWC fell below the set point.

Contour graphs for a sunny day as well as a cloudy day were constructed using VWC sensor readings for all treatments. Results from the cloudy day graphs were similar to those from the sunny day, so the cloudy day data were not reported. Results indicated

increasing moisture gradients within the walls from top to bottom, with the top being drier (Figure 2). These graphs provided a visual representation of VWC data. To analyze these results further, the VWC sensor readings were averaged into one reading per level. Results from this analysis indicated that the top one-third portion of the wall in each treatment was significantly drier than lower two-thirds of the wall (Table 6). The middle and bottom of the wall for each treatment were not significantly different (Table 6).

The contour graphs indicate that the sensor-controlled treatment was drier overall than the other two treatments. To determine statistical differences, the overall VWC readings from the sensors were averaged and the results indicated that the sensor-controlled treatment was drier than the two ET rate treatments while the two ET rate treatments were not significantly different (Table 6).

Water use efficiency differed between irrigation treatments, based on the results in Table 5. Water use efficiency for the sensor-controlled treatment was more than nine times greater than both of the ET rate treatments (Table 5). These results suggest sensor-controlled irrigation could increase efficiency of water use since basil yield was the same across treatments.

There was an interactive effect on irrigation treatment and level within the wall on pore water EC (Table 7). The sensor-controlled irrigation treatment resulted in an EC gradient within the wall, with higher EC at the bottom of the wall (Table 7), suggesting nutrients were leached down from the top to the bottom of the wall as a result of the vertical water movement. These results were consistent with the water distribution results from the contour graphs showing a gradient of dry to moist from top to bottom. No clear EC gradient was present in either of the ET rate treatments (Table 7). This is

possibly due to a leaching affect in the two ET rate treatments leaving little EC to form a gradient.

The biggest treatment differences in EC were seen in the bottom level, with the sensor-controlled irrigation having more than double the EC of the other two treatments (Table 7). Additionally, EC readings at each level in the sensor-controlled treatment were higher than those at the same level in both ET rate treatments (Table 7). This suggests a greater amount of nutrients in the sensor-controlled wall than in the ET treatments since EC is related to nutrient content and a higher EC represents a greater amount of nutrients present.

These results suggest that sensor-controlled irrigation can not only produce the same yield as the other two treatments while using less water, but can also reduce the amount of nutrients lost from leaching. While leachate was not analyzed during this study to determine the amount of leaching or the nutrients leached, previous results indicated that less water was applied to the sensor-controlled treatment, which could also result in less nutrients lost. Burnett and van Iersel (2008) found similar results indicating that sensor-controlled irrigation systems can apply less water resulting in less leachate, while still maintaining adequate plant growth in their study on irrigation efficiency with capacitance sensor-controlled irrigation.

Conclusion

The soilless/compost substrate was found to be a viable substrate for green wall systems based on its high PAW, high water content after saturation, low bulk density, and sustainability. While the green roof substrate may be viable for green roofs, for purposes

of this study, it was unable to hold as much water, had lower PAW, and a higher bulk density than the soilless or soilless/compost substrates. While the soilless/compost substrate was not significantly different than the soilless substrate with respect to PAW, it can be seen as a more sustainable substrate option for green wall systems, as compost is often a locally available and cheap or free product.

Sensor-controlled irrigation was found to require 386 L (one-time ET) and 281 L (multiple time ET) less water, with the same yield as conventional watering techniques. This suggests a reason to use a sensor-controlled system; one, which is accessible to growers and easy to program, without sacrificing the accuracy of more complex systems. Sensor-controlled irrigation not only is more efficient in terms of water use, but it also reduces the amount of nutrient leaching from the substrate within the green wall system. This reduction resulted in a greater amount of nutrients remaining in the wall. Sensor VWC readings confirmed these results as they indicated that the sensor-controlled irrigation treatment was overall drier than the two ET rate treatments.

Water distribution was found to be similar among treatments. The top level was drier than the middle and the bottom, while the middle and bottom were similar. Continued efforts are necessary to further investigate an irrigation schedule or system that will evenly distribute water throughout the green wall system.

Several aspects of this research have implications for using green walls for urban farming. While differences in yield between the two sides of the wall had no negative results in this study, this could be an issue in an urban environment where a green wall could be shaded by trees or adjacent buildings, resulting in a substantially reduced harvest. Additionally, this research provides an opportunity for urban farmers to evaluate

various substrates on-site. Given there is a wide range of substrates for use in green wall systems, urban farmers can determine a suitable substrate based on bulk density and PAW by using the simple and straightforward methods outlined in this study. Finally, this research presents an opportunity to develop a low-cost, easy to operate sensor-controlled irrigation system for urban farming in green walls.

Figure. 1. Green wall system design.

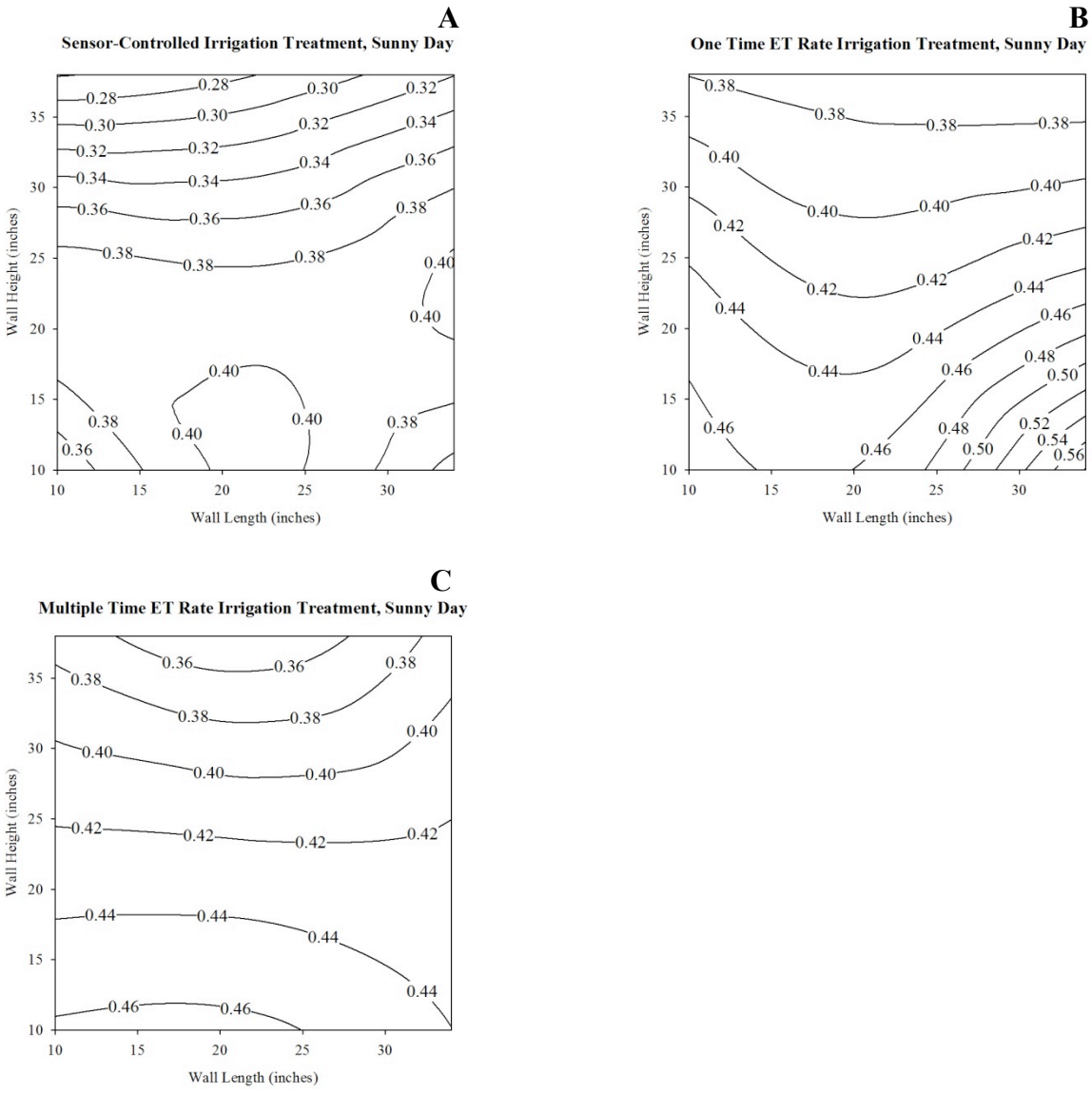

Figure. 2. Contour graphs of volumetric water content in green walls on a sunny day for three irrigation treatments: (A) sensor-controlled, (B) one time ET rate, (C) multiple time ET rate.

Table 1. Mean plant available water (PAW), plant unavailable water, and water holding capacity for three substrate treatments and their significance.

Treatment	PAW	Plant unavailable water	Water holding capacity
	m^3/m^3		
Green roof	0.326 b[z]	0.020 b	0.356 b
Soilless	0.535 a	0.040 a	0.575 a
Soilless/compost	0.524 a	0.044 a	0.568 a
Significance	<0.001	<0.0001	<0.0001

[z]Means with the same letter within a column are not significantly different ($P > 0.05$).

Table 2. Mean bulk density for three substrates and their significance.

Treatment	Bulk Density
	g/cm^3
Green roof	1.02 a[z]
Soilless	0.19 c
Soilless/compost	0.27 b
Significance	<0.0001

[z]Means with the same letter are not significantly different ($P > 0.05$).

Table 3. Mean basil fresh weights from irrigation scheduling treatments and wall side in green wall system and their significance for three harvests.

Treatment	Harvest 1	Harvest 2	Harvest 3
	Basil g/wall		
Irrigation treatment			
Sensor-Controlled	120	2,606	430
One-Time ET	151	2,510	384
Multiple Time ET	106	1,552	361
Significance	0.11[z]	0.07	0.13
	Basil g/side		
Wall side			
East	70.7	1,484	256
West	55.2	739	135
Significance	0.0011	<0.0001	<0.0001
Side * Irrigation	0.19	0.08	0.09

[z]Means are not significantly different at ($P > 0.05$).

Table 4. Interactive effect of wall level and wall side on mean basil fresh weights for green wall system from Harvest 3.

Treatment	**Harvest 3**	
	Wall Side	
	East	West
Level	Basil g/level	
Top	24.6 b[z]	16.4 c
Mid 1	35.1 a	12.6 cd
Mid 2	26.3 b	16.7 c
Bottom	16.5 c	8.5 d
Level * Side	0.007	

[z]Means with the same letter are not significantly different ($P > 0.05$).

Table 5. Mean total water use and water use efficiency (basil fresh weight/water use) for the three irrigation scheduling treatments and their significance.

Treatment	**Total water use**	**Water use efficiency**
	liters	g/L
Irrigation treatment		
Sensor-Controlled	68.7 b[z]	53.1 a
One-Time ET	454.2 a	6.8 b
Multiple Time ET	349.4 a	6.4 b
Significance	0.005	0.005

[z]Means with the same letter within a column are not significantly different ($P > 0.05$).

Table 6. Overall mean volumetric water content (VWC) for each irrigation treatment and mean VWC for each level sensors were placed in wall.

Treatment	**Overall Volumetric Water Content**
	(m^3/m^3)
Irrigation treatment	
Sensor-Controlled	0.345 a[z]
One-Time ET	0.426 b
Multiple Time ET	0.416 b
Significance	0.0017[y]
	Volumetric Water Content
	(m^3/m^3)
Level	
Top	0.342 b[z]
Middle	0.421 a
Bottom	0.425 a
Significance	<0.0001
Level * Irrigation	0.290

[z]Means with the same letter are not significantly different ($P > 0.05$).
[y]Means are not significantly different at ($P > 0.05$).

Table 7. Interactive effect of wall level and irrigation scheduling treatment on mean pore water electrical conductivity (EC) readings for green wall system.

	Pore Water EC		
	Irrigation treatment		
	Sensor-controlled	One-Time ET	Multiple Time ET
Level	($mS \cdot cm^{-1}$)		
Top	1.28 c[z]	0.85 d	0.84 d
Mid 1	1.29 c	0.60 ef	0.56 f
Mid 2	1.91 b	0.79 de	0.79 def
Bottom	2.31 a	1.01 d	0.97 d
Level * Irrigation	<0.0001		

[z]Means with the same letter are not significantly different ($P > 0.05$).

CHAPTER 3

CONCLUSIONS

Based on harvest data, sunlight exposure of green wall systems is an important consideration. The test walls were planted on a north-south orientation to balance light between sides as uniformly as possible. However, in this study, the west side was partially shaded by a nearby stand of trees, casting a greater shadow than expected. The un-shaded east side yielded twice the basil as the west side. The shaded situation of the study site is not unlike typical green wall sites in urban environments, where buildings could cast a similar shadow, effecting plant growth and yield. From these results, further research is needed with green walls built facing all directions, comparing harvest yields with measured light levels.

Basil was chosen as the crop to grow in the walls for the irrigation treatment study based on weather conditions during the time of the study, its quick growth habit, and its resilience to extreme water conditions. The lack of differences seen in basil harvested among the treatments could be attributed to the ability of basil to grow in both wet and somewhat dry conditions. If other vegetable crops or herbs were grown in the walls, which were more sensitive to varying moisture conditions, yields could vary. These findings present opportunities for further research into crops suitable for planting into

green wall systems, as well as crops suitable for evaluating yields from irrigation system or scheduling treatments.

As seen in the contour graphs (Figure 2), water distribution varied among the wall levels, with similar trends in each treatment. Results indicated that for all treatments, the top level was drier than the middle and bottom, while the middle and bottom were similar; however, the contour graphs seem to express more differences in water distribution, which are not explained statistically. To investigate these visual differences more sensors could be placed throughout the wall, or plants could be planted at a denser spacing to better determine water distribution patterns if they exist.

Additionally, alternative irrigation systems could be explored to further investigate water distribution. Clearly, spacing of drip tubing and emitters within a green wall system will have an impact on water distribution within a wall. The actual amount of variability will depend on how the water is applied, and is likely to vary with specific substrate mixes and the physical properties of those substrates. To address these distribution issues, different types of irrigation systems, in addition to schedules, should be evaluated. Specifically a system could be evaluated that would re-route water draining to the bottom from the top. This could potentially be done by compartmentalizing sections of the wall to prevent water from the top section from entering the bottom. This water could be captured and redistributed as needed.

To further investigate water distribution in green walls, a more moisture sensitive crop could be used, as discussed above. In addition to it potentially showing differences in yield among treatments, it could also be used to determine where there were water distribution differences in the wall itself.

Crop planting density could also be explored in investigating water distribution. By planting at a higher density, plants would potentially use more water, reducing distribution differences.

The use of sensor-controlled irrigation has been shown to be a viable option in developing irrigation schedules and systems for green wall systems. Not only to signal an irrigation event, but also to monitor systems and schedules evaluated for water distribution in green walls. User friendly and economically affordable systems should be explored to incorporate this technology into green wall systems.

Water conservation is just as important as yield when comparing results of different treatments. Although this study was not able to show differences in basil yield between the treatments, it did show how a sensor-controlled irrigation system can be incorporated into a green wall system to reduce the amount of water applied to the system and to use it more efficiently to conserve water without sacrificing the basil yield. Sensor VWC readings confirmed these results as they indicated that the sensor-controlled irrigation treatment was overall drier than the two ET rate treatments, while containing more nutrients.

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