Effects of Maintained Substrate Water Contents on Bedding Plant Production

by

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Abstract

Growers differ on the ideal substrate moisture content for early stages of bedding plant production. The studies presented in this thesis were conducted to evaluate the effects of substrate moisture content on growth of two bedding plant species [*Impatiens walleriana* (Hook.f) and *Catharanthus roseus* (L.)] when not thoroughly watered in at potting and the feasibility of adopting this system for producer use.

The objective of the experiment in Chapter 2 was to determine the effects of substrate water content on *Impatiens walleriana* 'Xtreme Red' in early production stages and to determine depth of root growth within the container at varying substrate water contents. Five irrigation treatments [64%, 68%, 72%, 76% and 80% gravimetric water content (GWC)] were evaluated for their effect on growth of *Impatiens walleriana* 'Xtreme Red' growing in Fafard 3B potting mix. Size index, shoot dry weight, and root dry growth increased with increasing GWC. Plants in the 80% GWC treatment contained the greatest root dry weight within the bottom half of the substrate profile.

In the experiments described in Chapter 3, five irrigation treatments (78%, 80%, 82%, 84% and 86% GWC) were evaluated for their effects on the growth of *Catharathus roseus* 'Pacifica Deep Orchid' and *Impatiens walleriana* 'Xtreme Orange' grown in an 80 peat : 20 perlite substrate (by vol.). Size index, shoot dry weight, and root dry weight of impatiens increased with increasing substrate GWC. Impatiens in the 86% treatment contained the greatest number of roots within the bottom half of the substrate profile. Size index, shoot dry weight, and root dry weight of annual vinca were not affected by substrate GWC.

In the experiments described in Chapter 4, substrate was irrigated daily to 70%, 74%, 78%, 82% or 86% GWC during early weeks of production and placed in one of two irrigation regimes (simulated wet/dry cycle and continually wet) during the final weeks of production. The objectives were to determine the effects of irrigation regime on growth of *Impatiens walleriana* 'Xtreme Orange' and *Catharanthus roseus* 'Pacifica Deep Orchid' in early production stages when not thoroughly watered in at potting and to determine effect of irrigation regimes on depth of root growth within the container. There was a quadratic response between target GWC and annual vinca size index, shoot dry weight, and root dry weight. Annual vinca in the drier treatments (70% and 74% GWC) throughout the entire production cycle were larger compared to the plants no subjected to the wet/dry cycle. There was no difference between target GWC and impatiens size index or height. Impatiens in the driest treatment (70%) throughout the entire production cycle were taller when compared to all other treatments.

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GWC	Gravimetric water content
VWC	Volumetric water content
DAP	Days after potting
WAP	Weeks after potting
SDW	Shoot dry weight
RDW	Root dry weight
SI	Size Index

Chapter 1

Introduction and Literature Review

For census year 2007, total wholesale sales for wholesale and nursery crop growers reached $16.9 billion in fiscal year 2006 (U.S. Department of Agriculture, 2007). In 2012, floriculture item sales at all retail outlets was $34.3 billion while the wholesale value of all floriculture crops rose slightly in 2012 to $4.1 billion for growers in the top 15 states that were surveyed. The total floriculture production area for the 15 states that were surveyed in the census totaled 49,877 acres (U.S. Department of Agriculture, 2012). The average floriculture value for wholesale products per acre was estimated to be $84,608. For growers to obtain high production values, intensive production methods are required, including frequent irrigation and fertilizer applications.

Water is a finite resource, and agriculture places the greatest global demand on freshwater resources (Moe and Rheigans, 2006). According to the International Water Management Institute, over 70% of the world's developed water supplies are used for irrigation (Seckler et al, 1998). Global water use has risen dramatically over the past 50 years due in part to the demand for irrigated agriculture as well as population growth. There is growing recognition that increasing water scarcity threatens agricultural production, human health and political stability in many parts of the world. At current rates, water use is not sustainable (Moe and Rheingans, 2006). As demand for irrigation water increases, growers will need to find a way to continue to produce high quality bedding plants with declining irrigation water supplies (Beeson et al., 2004). According to Biernbaum (1992), the large amounts of water that are consumed and released into the environment have been due in part to the cultural practices that have been developed over the last few decades. Water requirements of food crops and turfgrass have been reported, but data quantifying the irrigation requirements of ornamental landscape plant production are minimal.

There is a common consensus among growers that irrigation at retail garden centers is almost never optimal to the irrigation the plants received at the producers. This phenomenon can be traced to the use of untrained individuals as well as understaffing at retail garden centers. Watering regimes at retail stores can vary between two extremes: either plants are watered on a set schedule regardless of need which can result in plants either being over or under-watered or plants are left to wilt between irrigation events. Both scenarios are detrimental to plant health and can help to hasten the decline in both postharvest quality and shelf life at the retail market level (Starman et al., 2007). Hardening off, or toning, is often implemented at the end of the greenhouse production cycle by reducing fertilizer rates and exposing to varying levels of temperature, light intensity and soil moisture levels. This process has long been known to increase the shelf life of many floriculture crops including chrysanthemum, poinsettia as well as other bedding plants (Jones, 2002.) Reducing the irrigation volume during the entire production time and not only at the hardening- off stage may serve to better acclimate floriculture crops to the drought stress they may be exposed to during marketing. Starman et al. (2006). provides the example that when irrigation was withheld in both salvia and annual vinca until wilting for two consecutive drying cycles, both species had a higher water use efficiency (WUE) during the second drying cycle compared with the first, indicating there was a physiological acclimation of the plants. Williams et al. (2000) found that by comparing four water levels that were applied throughout production of two cultivars of potted miniature roses [*Rosa ×hybrida* (L.) ‘Charming’ and ‘Bianca Parade’], it was found that plants were better able to survive periods of inadequate water during postproduction when water consumption was lower during production. The inverse was also true: rose plants watered at the highest water level had higher water contents but tended to wilt sooner than plants grown with reduced water. Armitage and Kowalski (1983) found that petunias that were grown at three irrigation frequencies during the production cycle and were then evaluated at three post-production temperatures (10/10, 20/20, and 30/20 °C day/night) declined most rapidly in quality and had the greatest number of senesced flowers in the moderate and warm postproduction environments when they were irrigated at the highest frequency. Inversely, plants irrigated less frequently had slower flower development but had reduced number of senesced flowers, greater dry weights, and overall better visual quality regardless of the postproduction temperature to those plants that were irrigated more frequently.

One way the industry can reduce the use of overwatering is the adoption of soil moisture sensor (SMS) technologies. Soil moisture sensors have emerged as a mechanism for implementing precise irrigation in intensive agriculture. SMS measure substrate moisture status in real time. Substrate moisture data can be used by growers to determine irrigation volumes and intervals. Furthermore, substrate moisture data can be used by automated systems to control the timing, amount, and duration of irrigation required to replenish the water in a growing substrate to a preset level. SMSs can be utilized to align irrigation scheduling with evapotranspiration, substrate water changes and rainfall in container production environments (Lea-Cox et al., 2013). Utilizing SMSs in this way can greatly reduce irrigation water consumption compared to the industry standard practice of static, timer based irrigation without risking adverse effects that may happen from under- and overwatering resulting in fertilizer savings as well as water delivery (i.e. pump operations.) (Majszertik et al., 2013). Warsaw et al. (2009) state that the use of static timers for control does not account for the day-to-day changes in plant water use efficiency compared to calculating and returning the substrate to container capacity. In a study, they used manual substrate water measurements to calculate and apply the water used the previous day (Daily Water Use=DWU) resulting in a 27- 70% decrease in water use without impacting plant growth on list the taxa here.

There are multiple ways to monitor plant water demand. The research presented here uses substrate-based monitoring. The key to substrate based watering is carefully monitoring the substrate water status. In addition to water potential, water content is another expression used to describe the water status within a given substrate (Kirkham, 2005). Substrate water content can be measured in two ways: gravimetrically or volumetrically. Gravimetric water content is the ratio of the mass of water to the mass of substrate. Volumetric water content, usually noted as theta (θ), is the ratio of the volume of water to the volume of substrate. For scheduling irrigation, substrate water content is the most valuable measurement among plant or substrate based monitoring methods (Jones, 2007). The use of electrical probe moisture sensors that measure electrical properties within the substrate to quantify volumetric water content has gained popularity (Ferreras et al., 2003).

Utilizing the moisture content of substrate to control irrigation cycles is relatively easy to apply in practice (Jones, 2004). An automated system that constantly monitors substrate water status can be used to control both irrigation volume and frequency and has been coined on-demand irrigation (Owen et al., 2008). However, utilizing substrate moisture sensors is not without its problems. According to Ferreras et al. (2003), knowledge is limited on how substrate data obtained from soil moisture sensors correlates to plant performance. Since the physical properties of substrates may change over time (i.e. decomposition of components as well as overall root growth fills the container), sensors may need to be recalibrated multiple times throughout the production cycle of crops (Ferreras et al, 2003) In a paper by Altland (2006), he states that another limitation to using sensors is the fact that the substrate moisture content is not evenly distributed throughout the container. Therefore measuring only a small area relative to the size of the container may result in excessive or inadequate watering. Ferreras et al. (2003) came to the same conclusion by stating that the high variability of substrate water properties within the same container can limit the effectiveness of monitoring substrate moisture due to the small surface area of the measuring probe.

The gravimetric method is the oldest method for collecting data on substrate moisture Johnson (1962). The process of using gravimetric data to monitor the water content of the substrate during production has been utilized by researchers to predict water stress (Cabrera, 1997). Gravimetrically controlled on-demand irrigation can significantly reduce leaching and reduce the irrigation volume applied without reducing the quality of plants as compared to those plants grown under scheduled irrigation (Sammons and Struve, 2008). Under the gravimetric method of substrate monitoring, the only critical piece of information is the weight of the container at container capacity. Irrigation frequency and amount can then be determined by monitoring the change in weight.

The use of automatic systems can return the substrate to or close to container capacity (the maximum amount of water the substrate can hold against gravity), but it may be beneficial to use an irrigation system that can irrigate the substrate to a desired gravimetric or volumetric water content below container capacity. In a study by Nemali and van Iersel (2006), constant volumetric water content (VWC) was reliably maintained for impatiens, petunia, salvia and vinca for extend periods of time despite the variations of plant sizes with little to no runoff or water waste. An irrigation system that can maintain a substrate below container capacity and above the water content at which the crop begins to exhibit water stress would ensure that the crop has adequate water while avoiding excess leaching (Campbell and Campbell, 1982; Nemali and van Iersel, 2006; Burnett and van Iersel, 2008). Utilizing this type of irrigation system is beneficial for research on plant-water relations. Research in this area provides growers with ways to reduce water use during production by providing the plant only with the water needed to maintain both quality and health throughout the growing and retail process (Nemali and van Iersel, 2006). A study was conducted by van Iersel et al., (2010) in which they utilized a soil moisture sensor-controlled irrigation system to quantify the daily water use (DWU) of petunia in VWC's ranging from 5% to 40%. They reported that lower VWC resulted in decreases in shoot dry weight and leaf water potential, as well as observing only a slight additional increase in growth above the 25% VWC (van Iersel et al., 2010). In a study conducted by Nemali and van Iersel (2008) found maintained substrate VWC at 9%, 15%, 22%, or 32%), gas exchange, chlorophyll fluorescence and leaf water potential were similar between 22% and 32% VWC for impatiens and salvia. Earl (2003) discovered that greenhouses along with frequent, automated irrigation to monitor and control substrate moisture content provide the ideal conditions for the utilization of gravimetric data since the conditions can be controlled.

Many studies have been conducted to determine effects of substrate water content on bedding plant growth (van Iersel et al., 2010; Nemali and van Iersel, 2006). In these studies, newly planted plugs were thoroughly watered in at the beginning of the study. In the first few weeks of bedding plant production, growers will rarely irrigate to bring the substrate up to container capacity. Although growers do not regularly irrigate to container capacity in early stages of bedding plant production, growers differ on the ideal substrate moisture content for early stages of bedding plant production. It is commonly assumed that drier substrates cause roots to grow deeper into the container.

Since the start of horticulture research utilizing soilless substrates, the biggest observed contrast between soil and soilless systems that has been the confinement of the roots into a specific, well defined root zone (Raviv and Lieth, 2008). The smaller the root zone, the more intensive the production system needs to be to manage this volume. Numerous experiments and simulation studies demonstrated that a continuous growth process of the root system is essential to ensure efficient water and nutrient uptake from the substrate, which is critically important in the case of low mobility nutrients (e.g. P, Mn, Zn) (Raviv and Lieth, 2008). Plants growing in soil typically exhibit fine root growth to branch out and explore to gain access to water and nutrients from the less-explored regions of the root zone. This active, vital growth of soil-grown plants solely depends on continued formation of these new roots (Raviv and Lieth, 2008). In soilless culture, the frequent flushing of the root zone leads to a near absence of clear depletion zones which in turn diminishes the need by the plant to send out these “foraging” roots, and since the process of root growth is persistent, root systems of container-grown plants tend to be dense in nature (Raviv and Lieth, 2008).

By reducing overwatering, root systems of a containerized plant would theoretically expand throughout the container faster than a plant that is supplied with an overabundance of water. This in turn should lead to a plant that would be more tolerant of placement into the landscape than a plant with a dense root ball. Optimization of the soilless culture system will require that irrigation and fertilization be carried out with precision in both timing and location. Under conditions in which water and nutrients are in sufficient supply, the volume of substrate has little or no effect on the root-to-shoot ratio (Raviv and Lieth, 2008). An insufficient water and nutrients leads to a need for a greater root density to supply the canopy's need for water and nutrients which in turn leads to greater oxygen and nutrient consumption per unit volume of the root zone (Raviv and Lieth, 2008). This increase in oxygen and nutrient consumption results in intense root competition for oxygen and nutrients which leads to an increased decline in both dissolved oxygen (DO) and available nutrients. The reduction of available dissolved oxygen levels can negatively affect root function, increase susceptibility to diseases and eventually lead to death (Raviv and Lieth, 2008). If water is removed preferentially from areas with a high ratio of root biomass compared to those areas with lower ratios, pockets can develop within the substrate where concentrations of solutes can reach toxic levels to the plant and eventually lead to root death (Raviv and Lieth, 2008).

Growers have historically dealt with the problem of pockets containing these concentrated solutes by providing an excess amount of water that leaches from the root zone (Raviv and Lieth, 2008). By irrigating in this fashion, oxygen starvation can occur by removing the atmospheric O_2 from the root zone due to flooding (Raviv and Lieth, 2008). By allowing the root zone to dry out more between irrigation events and not allowing the root zone to stay constantly saturated, we can increase the availability of gas exchange that takes place within the root zone and lessen the susceptibility of the plant to diseases that can occur do to oversaturation (Raviv and Lieth, 2008).

By providing a way to supply only the water the plant needs during the early stages of production, producers can decrease the amount of leaching that occurs during the growing process which in turn saves money by decreasing water costs and decreases the potential of surface and groundwater contamination. This research will demonstrate the effects of varying levels of gravimetric water content on the early stages of crop production in a production environment. Furthermore, this research will explore the feasibility of adopting this method in a production setting and the effects of moisture contents on overall plant growth and development.

Literature Cited

Altland, J. 2006. Container no-brainer. Digger 47(11)48-53.

Armitage, A.M. and T. Kowalski. 1983. Effect of irrigation frequency during greenhouse production on the postproduction quality of *Petunia hybrida* (Vilm. J.) J. Amer. Soc. Hort. Sci. 108:118-121.

Beeson, R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hort. 22:113-115.

Biernbaum, J.A. 1992. Root-zone management of greenhouse container-grown crops to control water and fertilizer. HortTechnology 2:127-312.

Burnett, E. and M.W. van Iersel. 2008. Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance sensor-controlled irrigation. HortScience 43:1555-1560.

Cabrera, R.I. 1997. Comparative evaluation of nitrogen release patterns from controlled release fertilizers by nitrogen leaching analysis. HortScience 32:669-673.

Campbell, G.S. and M.D. Campbell. 1982. Irrigation scheduling using soil moisture measurements: Theory and practice. Advances in Irrigation 1:25-42.

Earl, H.J. 2003. A precise gravimetric method for simulating drought stress in pot experiments. Crop Science 43:1868-1873.

Fereres, E., D.A. Goldhamer, and L.R. Parsons. 2003. Irrigation water management of horticultural crops. HortScience 38:1036-1042.

Johnson, A.I. 1962. Methods of measuring soil moisture in the field. In Contributions to the hydrology of the United States. Washington, D.C.: U.S. Department of the Interior; U.S. Govt. Print. Off.

Jones, H.G. 2004. Irrigation scheduling: Advantages and pitfalls of plant-based methods. J. of Exp. Bot. 55:2427-2436.

Jones, H.G. 2007. Monitoring plant and soil water status: Established and novel methods revisited and their relevance to studies of drought tolerance. J. of Exp. Bot. 58:119-130.

Jones, Michelle L. 2002. Postproduction care and handling. Ohio Florists' Assn. Bul. 872:15- 16.

Kirkham, M.B. 2005. Principles of soil and plant water relations. Elsevier. Burlington, MA.

Lea-Cox, J. D., W.L. Bauerle, M.W. van Iersel, G.F. Kantor, T.L. Bauerle, E. Lichtenberg, D.M. King, and L. Crawford. 2013. Advancing wireless sensor networks for irrigation management of ornamental crops: An overview. HortTechnology 23:717-724.

Majsztrik, J. C., E.W. Price, and D.M. King. 2013. Environmental benefits of wireless sensor-based irrigation networks: Case-study projections and potential adoption rates. HortTechnology. 23:783-793.

Moe, C.L. and R.D. Rheingans. 2006. Global challenges in water, sanitation and health. J. of Water and Health 4:41-57.

Nemali, K.S. and M.W. van Iersel. 2008. Physiological responses to different substrate water contents: Screening for high water-use efficiency in bedding plants. J. Amer. Soc. Hort. Sci. 133:333-340.

Nemali, K.S. and M.W. van Iersel. 2006. An automated system for controlling drought stress and irrigation in potted plants. Scientia Hort. 110:292-297.

Owen, J. Jr, A. Prehn, S. Warren, and T. Bilderback. 2008. Comparing conventional to on-demand gravimetric based irrigation scheduling for containerized nursery crops. Proc. Southern Nurs. Res. Conf. 53:535-538.

Raviv, and J. Lieth. 2008. Soilless culture: Theory and practice. 1st ed. Elsevier. Burlington, MA.

Sammons, J.D. and D.K. Struve. 2008. Monitoring effective container capacity: A method for reducing over-irrigation in container production systems. J. Environ. Hort. 26:19-23.

Seckler, David, U. Amarasinghe, D. Molden, R. De Silva, and R. Barker. 1998. World water demand and supply, 1990 to 2025: Scenarios and Issues. International Water Mgt. Inst. Rpt. 19.

Starman, T. and L. Lombardini. 2006. Growth, gas exchange, and chlorophyll fluorescence of four ornamental herbaceous perennials during water deficit conditions. J. Amer. Soc. Hort. Sci. 131:469-475.

Starman, T.W., S.E. Beach, and K.L. Eixmann. 2007. Postharvest decline symptoms after simulated shipping and during shelf life of 21 cultivars of vegetative annuals. HortTechnology 17:544-551.

United States Department of Agriculture. 2012. Census of Agriculture. NASS - National Agricultural Statistics Service. Washington. 20 Apr. 2015. <https://www.agcensus.usda.gov/Publications/2012/>

United States Department of Agriculture. 2007. Census of Agriculture. NASS - National Agricultural Statistics Service. Washington. 20 Apr. 2015. <https://www.agcensus.usda.gov/Publications/2007/>

van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45:277-282

Warsaw, A. L., R.T. Fernandez, B.M. Cregg, E. Lansing, and J.A. Andresen. 2009. Water conservation, growth, and water use efficiency of container- grown woody ornamentals irrigated based on daily water use. HortScience 44:1308-1318.

Williams, M.H., E. Rosenqvist, and M. Buchhave. 2000. The effect of reducing production water availability on the post-production quality of potted miniature roses (*Rosa ×hybrida*). Post-harvest Biol. Technol. 18:143-150.

Chapter 2

Effects of Substrate Gravimetric Water Contents from Transplant to Finished Stage on *Impatiens walleriana* 'Xtreme Red'

Abstract

Growers differ on the ideal substrate moisture content for early stages of bedding plant production. In this experiment, Fafard 3B was maintained at five GWC levels from potting to determine effects of *Impatiens walleriana* 'Xtreme Red' (Hook.f) growth as well as depth of rooting within substrate profile. Plugs were potted into 15.2 cm containers and irrigated initially to 64%, 68%, 72%, 76% or 80% GWC. An increase in GWC resulted in an increase in size index, shoot dry weight, and root dry weight. Substrate maintained at 80% GWC resulted in the highest percentage of roots in the bottom half of substrate profile. Results may differ in finer textured substrates that have less air space.

Introduction

Growers rarely irrigate bedding plant crops to bring the substrate up to container capacity (the point at which the substrate can hold no more water against gravity) (Lea-Cox, 2016). Research has been carried out to determine effects of substrate water content on bedding plant growth (van Iersel et al., 2010; van Iersel and Nemali, 2004; Cai and Starman, 2014). van Iersel and Nemali (2004) found that marigolds exposed to drought stress were more compact in their growth habit compared to those with adequate moisture. Plants in the high moisture treatments produced more dry mass and a higher leaf area per unit of length of stem compared to those in the low moisture treatments (van Iersel and Nemali, 2004). van Iersel et al. (2010) determined effects of substrate water content on Petunia ×hybrida. The substrate was maintained at or above substrate volumetric water contents (VWC; cm^3 water·cm^{-3} substrate) 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40. Shoot dry weight increased quadratically with VWC. There was a small increase in shoot dry weight between 25% and 40% VWC. All plants were uniformly watered for the first nine days after being transplanted into the containers, and it took nine days after irrigation treatment initiation for the substrate to reach the 0.05 VWC target. The substrate water content maintained during the first nine days is not reported. Substrate water content at container capacity was also not reported. Therefore, it is not known how 0.40 VWC (the wettest treatment) compares to container capacity in the substrate and size of container used in the study. Although growers do not regularly irrigate to container capacity in early stages of bedding plant production, growers differ on the ideal substrate moisture content for early stages of bedding plant production (Lea-Cox, 2016).

The objectives of this research were 1) to determine the effects of substrate water content on *Impatiens walleriana* ‘Xtreme Red’ in early production stages when not thoroughly watered in at potting and 2) to determine depth of root growth within the container at varying substrate water content.

Materials and Methods

This study took place at the Paterson Greenhouse Complex on the campus of Auburn University. On 9 July 2015, Fafard 3B was amended with 3.6 $kg \cdot m^{-3}$ (6 lbs·yd-3) of 3-4-month Osmocote Plus 15-9-12 (15N-3.9P-10K, Scotts Co., Maryville, OH). Six 15.2 cm containers (Dillen Products, Middlefield, OH) were filled loosely to the rim and dropped five times on a table to settle the substrate 1.6 cm below the rim. The containers were then weighed, and minor adjustments were made to bring the mass of substrate in each container to 322 g. After the six containers were filled, remaining substrate was placed into a 0.11 m^3 plastic bin (Sterlite Corp., Townsend, MA), sealed with plastic sheeting and placed into a walk-in cooler to maintain the moisture content. Containers were uniformly watered and placed into a cool, dark room to drain to determine container capacity. Containers were weighed, placed in a forced air-drying oven at 60 °C for two days and weighed again. It was determined that the containers held 136 g dry substrate on average, and the average gravimetric water content (GWC; g water·g $substrate^{-1}$) at container capacity was 81%.

On 14 July 2015, forty 15.2 cm containers were filled with 332 g of the Fafard 3B substrate that had been sealed. *Impatiens walleriana* 'Xtreme Red' that were sown on 15 June 2015 in a 200-cell plug tray were acquired from Young's Plant Farm, Inc. (Auburn, AL). Ten plugs were randomly pulled from the flat to determine the average fresh weight per plug (4.1 g). One plug was transplanted into each container. Containers were placed in a temperature-controlled greenhouse maintained between 18 °C and 34 °C for the duration of the experiment. Each container was weighed to determine the volume of water needed to bring the container to a target GWC of 80%, 76%, 72%, 68%, or 64%. Although substrate GWC at container capacity was 81%, a target GWC of 80% was selected as the highest target GWC to minimize leaching. The weight of each container at its target GWC was calculated by dividing the dry weight of Fafard 3B in each container by 1 minus the target GWC and adding the empty container weight and the average plug fresh weight [136.2 g ÷ (1-target GWC) + empty container weight + 4.1 g]. The volume of water needed to bring each container to its target weight was slowly distributed evenly across the surface using a 60-mL syringe directly after placing containers in the greenhouse. This process was repeated daily between 8:00AM and 10:00AM to bring each container to the Target GWC.

Each treatment had eight replications. The experimental design was a completely randomized design, and containers were spaced 15.2 cm on center on a greenhouse bench. Plant size was recorded weekly by calculating size indices for all plants [(height + widest width + perpendicular width) ÷ 3)]. Four plants per treatment were harvested three weeks after potting (WAP) on 4 Aug.2015. Shoots were harvested and placed in a forced air-drying oven at 60 °C until dry to determine shoot dry weights. The harvested containers were hand watered to container capacity and left to sit in a dark, cool room for two hours. The containers were then weighed to determine the weight at container capacity. Substrate pH and electrical conductivity (EC) were measured with a Hatch® Pocket Pro+ Multi 1 Tester Ph/EC meter (Hach Company, Loveland, CO) using leachate samples collected using the pour-through method (Wright, 1986). Containers were placed in a freezer at -2 °C. On 6 Aug. 2015 the average shoot weight of harvested replications for each treatment was calculated and added to the formula for the target weights of the remaining replications in place of the initial plug weight. The remaining plants were harvested in a similar manner 6 WAP on 25 Aug. 2015. Once root balls were thoroughly frozen, a machete and rubber mallet were used to divide root balls in half top from bottom. Root balls averaged 8.9 cm in height. Roots were washed and dried in a forced air-drying oven at 60 °C until dry and weighed to determine root dry weights. All data was analyzed using regression analysis within JMP statistical software (SAS Institute Inc., Cary, NC).

Results

Size index (SI) increased linearly and quadratically with target GWC 1 and 2 WAP (Table 2.1). SI increased linearly at the 0.05 α level with target GWC 3, 4, and 5 WAP. By 6 WAP there was a strong quadratic and linear relationship ($\alpha = 0.001$) between SI and target GWC. SI 6 WAP ranged from 20.0 to 21.9 among plants in target GWC treatments between 64% and 76% and sharply increased to 27.2 among plants in the 80% target GWC.

Shoot dry weight (SDW) 3 WAP ranged from 0.65 to 0.75 g among plants in target GWC treatments between 64% and 76% and sharply rose to 1.18 g in the 80% target GWC treatment (Table 2.2). Roots of all plants were present only in the top 4 cm of the root ball 3 WAP. Thus, only total root dry weight is presented. There was no regression response between root dry weight (RDW) and target GWC 3 WAP.

At 6 WAP, SDW responded linearly and quadratically to target GWC at the $p \leq 0.001$ level (Table 2.3). The average weights increased from 4.35 to 6.50 g between 64% and 76% target GWC treatments and sharply rose to 9.33 g at the 80% target GWC treatment. There was no response for top dry root weight or total dry root weight to target GWC. However, bottom dry root weight increased linearly and quadratically with target GWC at the ($p \leq 0.05$) level. There was significantly greater root dry weight in the bottom half of containers in the 80% target GWC treatment compared to all other treatments.

Varying target GWC levels also affected the pH and EC levels in the substrate 3 WAP and 6 WAP (Table 2.4). At 3 WAP there was a strong linear and quadratic response pH to target GWC. The pH decreased linearly with target GWC. Target GWC had no effect on EC levels 3 WAP. There was a quadratic relationship at the $p \leq 0.05$ level between pH and target GWC 6 WAP. Substrate pH ranged between 4.48 and 5.25. There was a quadratic response at the 0.01 α level between substrate EC and target GWC. EC ranged from 5.12 to 6.56 $mS \cdot cm^{-1}$ between 64% and 76% target GWC treatments, while substrate EC measured only 1.85 $mS \cdot cm^{-1}$ in the 80% target GWC treatment.

Total irrigation volume applied per plant increased linearly and quadratically at the $p \leq 0.001$ level (Table 2.5). Irrigation volume applied per plant increased 12% between 64% and 68% target GWC, 13% between 68% and 72% target GWC and 5% between 72% and 76% target GWC. However, irrigation volume applied per plant increased 30% between 76% and 80% target GWC. Leachate volumes of 4 mL or less were collected in the 80% target GWC treatment during the first ten days of the experiment (data not shown). Other treatments did not leach during the experiment.

Discussion

Significant increases were detected for SDW 3 WAP, SI 6 WAP, SDW 6 WAP, and bottom root dry weight 6 WAP between 76% and 80% target GWC. As stated earlier, growers typically do not irrigate to container capacity. Although containers in the 80% target GWC treatment were irrigated to a level close to container capacity daily, the substrate dried considerably between irrigation events due to high daily temperatures. Water became a limiting factor at the 76% GWC (32% VWC) levels. The sharp decrease in EC in the 80% treatment may be the result of two possibilities. The first being that plants in the 80% GWC level grew larger and demanded more water. The second possibility is that the increased amount of water in this treatment could result in the nutrients contained within the substrate to be diluted, resulting in easier take-up. Results may differ at cooler temperatures. A moisture characteristic curve was developed for Fafard 3B using the modified long column method to relate GWC to VWC (Altland et al., 2010). Target GWC levels of 64%, 68%, 72%, 76% and 80% relates to VWC levels of 0.07, 0.12, 0.20, 0.32, and 0.47, respectively. In the study by van Iersel et al. (2010), shoot dry weights increased little between 25% and 40% VWC, while shoot dry weight in our study increased significantly between target GWC levels of 76% and 80% which relates to VWC levels of 0.32 and 0.47. While plants in our study were irrigated once per day to bring substrate up to the target GWC, plants in the study by van Iersel et al. were irrigated on-demand when substrate water content dropped below the set VWC level (2010). Thus, substrate in the 76% target GWC treatment dropped to a GWC as low as 72% GWC between irrigation events which is equivalent to a VWC of 0.25. Substrate water contents at this level resulted in significantly less plant growth.

In this study, maintaining low substrate moisture contents directly after transplanting resulted in significantly smaller plants as soon as 2 WAP. Lower substrate water contents did not result in a higher percentage of total root growth in the bottom half of the container.

Literature Cited

Altland, J.E., J.S. Owen, and W.C. Fonteno. 2010. Developing moisture characteristic curves and their descriptive functions at low tensions for soilless substrates. J. Amer. Soc. Hort. Sci. 135:563-567.

Cai, X. and T. Starman. 2014. The effect of substrate moisture content on growth and physiological responses of two landscape roses (*Rosa hybrida* L.). HortScience 49:741-745

John Lea-Cox. 2016. When exactly should I irrigate? Greenhouse Product News, Sparta, MI. 13 April 2018. <https://gpnmag.com/article/when-exactly-should-i-irrigate/>

van Iersel, M. W. and K.S. Nemali. 2004. Drought stress can produce small but not compact marigolds. HortScience 39:1298-1301.

van Iersel, M.W., S. Dove, J.G. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45:277-282.

Wright, R.D. 1986. The pour-through nutrient extraction procedure. HortScience 21:227-229.

Table 2.1. Effects of target gravimetric water content (GWC) on size indices of *Impatiens walleriana* (Hook.f) 'Xtreme Red' transplants from 14 July to 25 Aug. 2015.

Target GWC	1 WAP[z]	2 WAP	3 WAP	4 WAP	5 WAP	6 WAP
64%	4.0	6.7	10.9	14.4	19.3	20.0
68%	4.4	7.5	11.3	15.5	19.5	20.4
72%	4.6	7.8	11.1	16.2	20.7	21.3
76%	4.5	8.1	11.8	16.4	20.8	21.9
80%	4.9	9.1	12.8	17.4	22.6	27.2
Significance[y]	L***Q**	L***Q***	L*	L*	L*	L***Q***

[z]Weeks after potting.
[y]Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***) level.

Table 2.2. *Impatiens walleriana* (Hook.f) 'Xtreme Red' dry shoot and root weights as affected by target gravimetric water content (GWC) from 15 July to 4 Aug. 2015

Target GWC	Shoot Dry Weight (g)	Root Dry Weight (g)
64%	0.65	0.90
68%	0.73	0.55
72%	0.75	0.50
76%	0.68	0.40
80%	1.18	0.55
Significance[z]	L*Q**	NS

[z] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*) or 0.01(**) level. NS= not significant.

Table 2.3. *Impatiens walleriana* (Hook.f) 'Xtreme Red' dry shoot and root weights as affected by target gravimetric water content (GWC) from 4 Aug. to 25 Aug. 2015.

		Roots		
Target GWC	Shoot Dry Weight (g)	Dry Weight Total (g)	Dry Weight Top (g)	Dry Weight Bottom (g)
64%	4.35	5.35	5.20	0.15
68%	4.63	4.30	3.53	0.78
72%	5.67	7.27	6.60	0.67
76%	6.50	5.30	5.08	0.23
80%	9.33	8.33	6.23	2.10
Significance[z]	L***Q***	NS	NS	L*Q*

[z] Significant linear (L)or quadratic (Q) trends using model regression at P ≤ 0.05 (*) or 0.001 (***) level. NS= not significant.

Table 2.4. Substrate pH and EC as affected by target gravimetric water content (GWC) for *Impatiens walleriana* (Hook.f) 'Xtreme Red' transplants from 15 July to 25 Aug. 2015

	3 WAP[z]		6 WAP	
Target GWC	pH	EC ($mS \cdot cm^{-1}$)	pH	EC ($mS \cdot cm^{-1}$)
64%	5.62	5.55	5.25	5.44
68%	5.53	6.17	5.04	6.56
72%	5.47	7.98	4.76	5.21
76%	5.14	5.95	4.48	5.12
80%	4.73	6.73	5.09	1.85
Significance[y]	L***Q***	NS	Q*	L*Q**

[z]Weeks after potting.
[y] Significant linear (L) or quadratic (Q) trends using model regression at P ≤ 0.05 (*), 0.01(**), or 0.001 (***) level. NS= not significant.

Table 2.5. Total average irrigation volume applied per plant as affected by target gravimetric water content (GWC) from 15 July to 24 Aug. 2015 on *Impatiens walleriana* (Hook.f) 'Xtreme Red'.

Target GWC	Irrigation Volume (mL)
64%	2134
68%	2392
72%	2696
76%	2843
80%	3690
Significance[z]	L***Q***

[z] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.001$ (***) level.

Chapter 3

Effects of Substrate Gravimetric Water Content from Transplant to Finished Stage on *Impatiens walleriana* (Hook.f) 'Xtreme Orange' and *Catharanthus roseus* (L.) 'Pacifica Deep Orchid'

Abstract

Growers differ on the ideal substrate moisture content for early stages of bedding plant production. In this experiment, an 80 peat : 20 perlite (by vol.) substrate was maintained at five substrate gravimetric water content (GWC) levels to determine effects on *Impatiens walleriana* (Hook.f) 'Xtreme Orange' and *Catharanthus roseus* (L.) 'Pacifica Deep Orchid' growth and depth of rooting in the substrate profile. Plugs were potted into 15.2 cm containers and irrigated initially to 78%, 80%, 82%, 84% and 86% substrate GWC. Plants were irrigated by hand daily using a 60-mL syringe to their target substrate GWC. Size index, shoot dry weight, and root dry weight increased with increasing GWC. Plants irrigated daily to 86% substrate GWC had the highest percentage of roots in the bottom half of the substrate profile. Growth of annual vinca was not impacted by target GWC over the course of the experiment.

Introduction

In the first few weeks of bedding plant production, growers rarely irrigate to bring the substrate up to container capacity (the point at which the substrate can hold no more water against gravity) (Lea-Cox, 2016). Research has been carried out to determine effects of substrate water content on bedding plant growth (van Iersel et al., 2010; van Iersel and Nemali, 2004; Cai and Starman, 2014; Jacobson et al., 2015). van Iersel and Nemali (2004) found that marigolds exposed to drought stress were more compact in their growth habit compared to those with adequate moisture. Plants in the high moisture treatments produced more dry mass and a higher leaf area per unit of length of stem compared to those in the low moisture treatments (van Iersel and Nemali, 2004). Water requirements of food crops have been quantified thoroughly while research into the water required to produce ornamental plants with healthy growth and a quality acceptable to growers and consumers has not been quantified as extensively (Henson et al., 2006). van Iersel et al. (2010) determined effects of substrate water content on *Petunia ×hybrida* (Hooker Vilmorin). The substrate was maintained at or above substrate volumetric water contents (VWC; $m^3 \cdot m^{-3}$ substrate) of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$. Shoot dry weight increased quadratically with VWC. There was a small increase in shoot dry weight between 25% and 40% VWC. All plants were well-watered uniformly for the first nine days after being transplanted into the containers, and it took nine days after irrigation treatment initiation for the substrate of the driest treatment to reach the 0.05 $m^3 \cdot m^{-3}$ VWC target. The substrate water content maintained during the first nine days is not reported. Furthermore, substrate water content at container capacity was not reported. Therefore, it is not known how 0.40 $m^3 \cdot m^{-3}$ VWC (the wettest treatment) compares to container capacity in the substrate and container used in the study.

Currently, the frequency and quantity of irrigation applied in most commercial nurseries is based on personal experience of the grower, or increasingly on the use of automated irrigation clocks (Beeson, 2004). This method does not take into consideration the daily water use of the plant, which can vary greatly from day to day, over the course of the growing season and as well as with overall plant growth. Growers rarely respond to these changes in water demand by modifying the irrigation regime so over- or under irrigation occurs with more frequency than what is required to supply the plant's needs (Grant et al., 2008).

The tools needed to schedule irrigation are well developed (Stirzaker, 2005). Tensiometers have been used for decades for monitoring soil water status and the recent adoption of capacitance devices that measure the dielectric property of the soil (Charlesworth, 2005) as well several methods of irrigation scheduling based on physiological responses to drying substrates exist (Jones, 2004). The use of these tools, however, have not been systematically adopted by growers (Grant et al., 2008). The reason for the failed adoption of these tools to monitor irrigation scheduling are unclear, but it may be that growers do not perceive them to work reliably under growing conditions. It may also be that growers cannot justify the time/expense that is associated with collecting, interpreting and subsequent implementation of the information that these systems provide (Grant et al., 2008; Stirzaker, 2003). Although growers do not regularly irrigate to container capacity in early stages of bedding plant production, growers differ on the ideal substrate moisture content for early stages of bedding plant production (Lea-Cox, 2016). Growers may conclude from these observations that drier substrates cause rooting more quickly into the container substrate.

The objectives of this research were 1) to determine the effects of substrate water content on *Impatiens walleriana* 'Xtreme Red' and *Catharanthus roseus* 'Pacifica Deep Orchid' in early production stages when not thoroughly watered in at potting and 2) to determine depth of root growth within the container at varying substrate water contents.

Materials and Methods

This study took place at the Paterson Greenhouse Complex on the campus of Auburn University. On 14 June 2016, 0.23 m^3 of peat was sifted through a 9.53 mm screen and combined with 0.057 m^3 of perlite to make an 80 peat : 20 perlite substrate (by vol.) that was mixed using a soil mixer (Mitchell Ellis Products Inc., Semmes, AL). The substrate was amended with 1.1 $kg \cdot m^3$ ground dolomitic limestone, 0.45 $kg \cdot m^3$ AquaGro®, and medium rate of Osmocote Classic® 3-4 month 14-14-14 (14N-6.1P-11.6K, Everris® US., Summerville, SC). The substrate was placed into two 0.11 m^3 plastic bins (Sterlite Corp., Townsend, MA) sealed with plastic sheeting, and placed into a walk-in cooler to maintain moisture content.

On 23 July 2016, seven 15.2 cm containers (Dillen Products, Middlefield, OH) were filled loosely to the brim and dropped 5 times on a table to settle the substrate to the lip 1.6 cm below the rim. The containers were weighed, and minor adjustments were made to bring the mass of substrate in each container to 295 g. After the six containers were filled, remaining substrate was re-sealed in the plastic bins to maintain the moisture content. Containers were thoroughly watered until the substrate held no more water and allowed to drain for 2 hours in a dark room to container capacity. Containers were weighed, placed in a forced-air drying oven at 60 °C for two days, and weighed again on 27 July 2016. It was determined that the containers filled from the first plastic bin contained 92.46 g (3.26 oz) dry substrate while the containers filled from the second plastic bin contained 92.55g (3.26 oz.). The average gravimetric water content (GWC; $g\ water \cdot g\ substrate^{-1}$) at container capacity was 86.8%.

On 27 July 2016, sixty 15.2 cm containers were filled with 295 g of the peat: perlite substrate that had been sealed. *Impatiens walleriana* ‘Xtreme Orange’ (impatiens) and *Catharanthus roseus* ‘Pacifica Deep Orchid’ (annual vinca) that were sown on 15 June 2016 in a 200-cell plug tray were acquired from Young’s Plant Farm, Inc. (Auburn, AL). Ten plugs of each species were randomly pulled from the flat to determine the average fresh weight per plug (4.1 g for both species). One plug was transplanted into each container. Containers were placed 15.2 cm apart on center in a temperature-controlled greenhouse maintained between 18°C and 34°C for the duration of the experiment. Each container was weighed to determine the volume of water needed to bring the container to a target GWC of 86%, 84%, 82%, 80%, or 78%. Although substrate GWC at container capacity was 86.8%, a target GWC of 86% was selected as the highest target GWC to limit leaching. The weight of each container at its target GWC was calculated by dividing the dry weight of substrate in each container by 1 minus the target GWC and adding the empty container weight and the average plug fresh weight [136.2 g ÷ (1-Target GWC) + empty container weight + 4.1 g]. The volume of water needed to bring each container to its target weight was slowly distributed evenly across the surface using a 60-mL syringe. This process was repeated daily between 8:00AM and 10:00AM to bring each container to the target GWC. Each treatment had six replications. The experimental design was a completely randomized design. Plant size was recorded weekly by measuring size indices (SI) for all plants [(height + widest width + perpendicular width) ÷ 3)].

Impatiens were harvested just 3 weeks after potting (WAP) on 17 Aug. due to *Fusarium* spp. problems, and annual vinca were harvested 5 WAP on 31 Aug. 2016. At harvest, shoots were harvested and placed in a forced air-drying oven at 60 °C until dry to determine shoot dry weights. The harvested containers were hand watered until substrate could hold no more water and left to sit in a dark, cool room for 2 h. The containers were then weighed to determine the weight at container capacity. Substrate pH and electrical conductivity (EC) were measured using leachate samples collected using the pour-through method (Wright, 1986). Containers were placed in a freezer set at -2 °C. Once root balls were thoroughly frozen, a chop saw (Ridge Tool Company, Elyria, OH) was used to divide the root balls in half. Root balls averaged 8.9 cm in height from top to bottom. Roots were washed and dried in a forced-air drying oven at 60 °C until dry and weighed to determine root dry weights (RDW). All data were analyzed using regression analysis within JMP statistical software (SAS Institute Inc., Cary, NC).

Results and Discussion

Target GWC had no effect on impatiens size indices (SI) 1 WAP, but SI increased linearly and quadratically with GWC at 2 and 3 WAP (Table 3.1). By 3 WAP, SI for impatiens ranged from 21.6 to 23.9.

Target GWC had no effect on annual vinca size indices one or 2 WAP, but size indices increased linearly and quadratically with target GWC 3, 4, and 5 WAP (Table 3.2). By 5 WAP, average size index of plants grown under a target GWC of 78% was only 4% lower than size index of plants grown under a target GWC of 86%. Average gravimetric water content at watering over the course of the experiment for impatiens watered to target GWC of 78%, 80%, 82%, 84%, and 86% was 61%, 64%, 67%, 71%, and 75%, respectively. Average gravimetric water content at watering over the course of the experiment for annual vinca watered to target GWC of 78%, 80%, 82%, 84%, and 86% was 60%, 64%, 67%, 72%, and 76%, respectively.

Average total irrigation volume applied per plant to impatiens increased linearly with increasing target GWC (Table 3.3). Irrigating the substrate to 86% GWC daily resulted in a 48% increase in irrigation volume applied compared to irrigating the substrate to 78% GWC daily.

Average total irrigation volume applied per plant to annual vinca increased linearly with increasing target GWC (Table 3.4). Irrigating the substrate to 86% GWC daily resulted in a 7% increase in irrigation volume applied compared to irrigating the substrate to 78% GWC daily.

Impatiens shoot and root dry weights increased linearly and quadratically at the $p \leq 0.01$ level 3 WAP (Table 3.5). Shoot dry weights ranged from 3.3 to 5.6 g from the 78% level to the 86% level respectively. The plants among the 84% treatment had an average dry weight of 5.8 g, which is 7% larger than the plants contained within the 86% treatment. Root total dry weights ranged from 1.09 to 2.28 g from the 78% treatment to the 86% treatment. Plants within the 82% treatment had an average total root dry weight of 2.32 g, which was 70% larger than plant in the 80% treatment. Dry weights for roots contained within the top 4.45 cm of the substrate column ranged from 1.01 to 1.56 g for the 78% and 86 treatments respectively. Dry weights for roots contained within the bottom 4.45 cm of the substrate profile ranged from 0.30 to 0.80 g from the 78% and 86% treatment levels respectively. For plants in the 80% treatment, 37% of the roots were contained within the bottom 4.45 cm of the substrate profile. No significant difference was detected for percentage of roots in bottom 4.45 cm of substrate for impatiens.

There was no response between annual vinca shoot dry weight, total root dry weight, top root dry weight, or bottom root dry weight and target GWC 5 WAP (Table 3.6). It is unknown if this result would have been the same if the vinca were harvested at 3 WAP. Given the extra two weeks, plants amongst all the treatments reached a uniform size regardless of the treatment to which they were assigned.

There was no response between substrate pH and target GWC 3 WAP among impatiens, however EC decreased linearly with increasing target GWC 3 WAP (Table 3.7). Values for EC were 2.1 $mS \cdot cm^{-1}$ among plants in the 78% target GWC treatment and decreased linearly to 0.9

$mS \cdot cm^{-1}$ among plants in the 86% target GWC treatment. These differences in EC values correlate to the amount of irrigation applied to plants daily. The greater the amount of daily irrigation means the greater concentration of nutrients dissolving into solution for uptake by the plant leading to a decrease in substrate EC. pH values for both impatiens and vinca were low due in part to only 1.134 kg./m^{-3} of dolomitic limestone being used instead of the industry standard of 2.27 kg./$m^{-3.}$

A strong linear and quadratic response at the $p \leq 0.001$ level was detected for pH at 5 WAP for annual vinca (Table 3.8). pH values ranged from 4.3 for the 78% treatment to 4.0 for plants in the 86% treatment. A linear response at the $p \leq 0.01$ level and a quadratic response at the $p \leq 0.05$ level was detected for EC at 5 WAP for annual vinca. EC values ranged from 1.9 $mS \cdot cm^{-1}$ for the 78% treatment to 1.3 $mS \cdot cm^{-1}$ for the 86% treatment.

Conclusion

During the experimental run of impatiens, we observed diminishing returns for shoot and root weight between the 80% and 82% treatment levels. Shoot weight increased 29% between 80% and 82% while total root dry weight increased 64% between these two treatments. It can be concluded that Target GWC has no effect on the percent of roots in the bottom half of the container. Target GWC also had no effect on annual vinca size over the course of the five-week experimental run.

Literature Cited

Beeson, Jr., R. C. 2004. Modeling actual evapotranspiration of *Ligustrum japonicum* from rooted cuttings to commercially marketable plants in 12-liter black polyethylene containers. Acta Hort. 664:71-77.

Cai, X. and T. Starman. 2014. The effect of substrate moisture content on growth and physiological responses of two landscape roses (*Rosa hybrida* L.). HortScience 49: 741-745.

Charlesworth, PB. 2005. Irrigation Insights No. 1. Soil water monitoring. National Program for Irr. Res. and Dev., 2nd ed. CSIRO Publishing, Melbourne.

Grant, M., M.J. Davies, H. Longbottom, and C.J. Atkinson. 2008. Irrigation scheduling and irrigation systems: optimizing irrigation efficiency for container ornamental shrubs. Irrig. Sci. 27:139-153.

Henson, D.Y., S.E. Newman, and D.E. Hartley. 2006. Performance of selected herbaceous annual ornamentals grown at decreasing levels of irrigation. HortScience 41:1481-1486.

Jacobson, A. B., T.W. Starman, and L. Lombardini. 2015. Substrate moisture content effects on growth and shelf life of *Angelonia angustifolia*. HortScience 50:272-278.

Jones, H.G. 2004. Irrigation scheduling: advantages and pitfalls of plant-based methods. J. Exp. Bot. 55:2427-2436.

Lea-Cox, John. 2016. When exactly should I irrigate? Greenhouse Product News, Sparta, MI. 13 April 2018. <https://gpnmag.com/article/when-exactly-should-i-irrigate/>

Stirzaker, R.J. 2003. When to turn the water off: scheduling micro irrigation with a wetting front detector. Irrig. Sci. 22:177-185.

Stirzaker, R.J. 2005. Managing irrigation with a wetting front detector. UK Irrig. 33:22-24.

van Iersel, M. W. and K.S. Nemali. 2004. Drought stress can produce small but not compact marigolds. HortScience 39:1298-1301.

van Iersel, M.W., S. Dove, J.G. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience. 45:277-282.

Table 3.1. Size indices of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC).

Target GWC	1 WAP[z]	2 WAP	3 WAP
78%	12.8	17.7	21.6
80%	12.4	17.6	21.8
82%	13.3	19.2	23.0
84%	13.1	19.8	23.8
86%	13.1	20.3	23.9
Significance[y]	NS	L***Q**	L**Q**

[z]Weeks after potting.

[y] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.01$(**) or 0.001 (***) level. NS= not significant.

Table 3.2. Size indices of *Catharanthus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC).

Target GWC	1 WAP[z]	2 WAP	3 WAP	4 WAP	5 WAP
78%	12.9	18.2	20.6	24.7	28.3
80%	13.6	18.4	21.3	25.3	29.3
82%	13.6	18.6	21.3	25.8	29.3
84%	12.9	18.5	21.1	26.1	29.3
86%	13.6	19.0	21.9	25.9	29.5
Significance[y]	NS	NS	L*Q**	L**Q**	L*Q*

[z]Weeks after potting.

[y] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*) or 0.01(**) level. NS= not significant.

Table 3.3. Average total irrigation volume applied per plant as affected by target gravimetric water content (GWC) from 27 July to 16 Aug. 2016 on *Impatiens walleriana* (Hook.f) 'Xtreme Orange.'

Target GWC	Irrigation Volume (mL)
78%	1523
80%	1730
82%	2068
84%	2205
86%	2258
Significance[z]	L*Q*

[z] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*) level.

Table 3.4. Average irrigation volume applied per plant as affected by target gravimetric water content (GWC) from 27 July to 31 Aug. 2016 on *Catharanthus roseus* (L.) 'Pacifica Deep Orchid'.

Target GWC	Irrigation Volume (mL)
78%	4304
80%	4418
82%	4379
84%	4621
86%	4596
Significance[z]	L*

[z] Significant linear (L) trends using model regression at $P \leq 0.05$ (*) level.

Table 3.5. *Impatiens walleriana* (Hook.f) 'Xtreme Orange' shoot and root weights as affected by target gravimetric water content (GWC) 3 weeks after potting.

		Roots				
Target GWC	Shoot Dry Weight (g)	Dry Weight Total (g)[z]	Dry Weight Top (g)[y]	Dry Weight Bottom (g)[x]	% Roots in Bottom	Shoot: Root Ratio
78%	3.26	1.09	1.01	0.30	28%	3.0
80%	4.24	1.36	1.15	0.50	37%	3.1
82%	5.38	2.32	1.52	0.80	34%	2.3
84%	5.77	2.09	1.49	0.61	29%	2.8
86%	5.57	2.28	1.56	0.72	32%	2.4
Significance[w]	L**Q**	L**Q**	L**Q*	L**Q**	NS	NS

[z] Total dry weight=Top dry weight + Bottom dry weight

[y] Dry weight of roots contained within top 4.45 cm of substrate profile.

[x] Dry weight of roots contained within bottom 4.45 cm of substrate profile.

[w] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*) or 0.01(**) level. NS= not significant

Table 3.6. *Catharanthus roseus* (L.) 'Pacifica Deep Orchid' shoot and root weights as affected by target gravimetric water content (GWC) 5 weeks after potting.

		Roots				
Target GWC	Shoot Dry Weight (g)	Dry Weight Total (g)[z]	Dry Weight Top (g)[y]	Dry Weight Bottom (g)[x]	Top: Bottom Ratio	Shoot: Root Ratio
78%	10.46	1.78	1.42	0.36	3.9	5.9
80%	10.69	1.85	1.49	0.36	4.1	5.8
82%	10.68	1.84	1.47	0.37	4.0	5.8
84%	11.24	1.85	1.47	0.38	3.9	6.1
86%	11.18	1.87	1.48	0.39	3.8	6.0
Significance[w]	NS	NS	NS	NS	NS	NS

[z] Total dry weight=Top dry weight + Bottom dry weight.

[y] Dry weight of roots contained within top 4.45 cm of substrate profile.

[x] Dry weight of roots contained within bottom 4.45 cm of substrate profile.

[w] Regression response non-significant (NS).

Table 3.7. Substrate pH and EC of *Impatiens Walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) 3 weeks after potting (WAP).

Target GWC	pH	EC ($mS \cdot cm^{-1}$)
78%	4.6	2.05
80%	4.6	1.37
82%	4.5	0.93
84%	4.6	0.96
86%	4.6	0.85
Significance[y]	NS	L***Q***

[z] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.001$ (***) level. NS= not significant.

Table 3.8. Substrate pH and EC of *Catharanthus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) 5 weeks after potting

Target GWC	pH	EC ($mS \cdot cm^{-1}$)
78%	4.3	1.91
80%	4.1	1.68
82%	4.1	1.46
84%	4.0	1.61
86%	4.0	1.34
Significance[y]	L***Q***	L**Q*

[z] Significant linear (L) or quadratic (Q) trends using model regression at $P \leq 0.05$ (*), 0.01(**), or 0.001 (***) level.

Chapter 4

Response of Root Development as Influenced by Varying Substrate Gravimetric Water Contents from Transplant to Finished Stages on *Impatiens walleriana* 'Xtreme Orange' and *Catharanthus roseus* 'Pacifica Deep Orchid'

Abstract

Growers differ on the ideal substrate moisture content for early stages of bedding plant production. In this experiment, an 80 peat: 20 perlite substrate (by vol.) was maintained at five GWC levels to determine effects of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' growth and *Catharanthus roseus* (L.) 'Pacifica Deep Orchid' as well as depth of rooting within substrate profile. Plugs were potted into 10.2 cm containers and irrigated initially to 70%, 74%, 78%, 82% and 100% GWC. Plants were irrigated by hand daily using a 60-mL syringe to bring the substrate to its target gravimetric water content (GWC). The experimental design was a randomized complete block with experimental run entered in the model as a random variable. For impatiens at 28 DAP, target GWC had no effect on size, height or root:shoot ratio Shoot dry weight of impatiens increased quadratically with increasing GWC. Root: shoot ratios for impatiens at 28 DAP was not significant. For annual vinca, size indices, shoot dry weight, and root dry weight at 49 DAP decreased quadratically with increasing GWC. Root:shoot ratios for annual vinca decreased linearly with increasing GWC. These results differ from previous studies in which decreasing substrate water content caused a proportional decease in both plant biomass and leaf area.

Introduction

In the first few weeks of bedding plant production, growers rarely irrigate to bring the substrate up to container capacity (the point at which the substrate can hold no more water against gravity) (Lea-Cox, 2016). Research has been carried out to determine effects of substrate water content on bedding plant growth (van Iersel et al., 2010; van Iersel and Nemali, 2004). van Iersel and Nemali (2004) found that marigolds exposed to drought stress were more compact in their growth habit compared to those with adequate moisture. Plants in the high moisture treatments produced more dry mass and a higher leaf area per unit of length of stem compared to those in the low moisture treatments (van Iersel and Nemali, 2004). van Iersel et al. (2010) determined effects of substrate water content on petunia [*Petunia* ×*hybrida* (Hooker Vilmorin)]. The substrate was maintained at or above substrate volumetric water contents (VWC; $cm^3 \cdot cm^{-3}$ substrate) of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40. Shoot dry weight increased quadratically with VWC. There was a small increase in shoot dry weight between 0.25 and 0.40 VWC. All plants were uniformly watered for the first nine days after being transplanted into the containers, and it took nine days after irrigation treatment initiation for the substrate to reach the 5% VWC target. The substrate water content maintained during the first nine days is not reported. Furthermore, substrate water content at container capacity was not reported. Therefore, it is not known how 0.40 $cm^3 \cdot cm^{-3}$ VWC (the wettest treatment) compares to container capacity of the substrate and container type used in the study.

Growers differ on the ideal substrate moisture content for early stages of bedding plant production (Lea-Cox, 2016). Kozlowski and Pallardy (2002) found that grown under water deficits (i.e. drier substrates) promote a greater allocation of photosynthates to root growth than those plants grown under optimal growing conditions. Research has been conducted which demonstrates that a deficiency of oxygen in the rhizosphere has an immediate effect on root growth, metabolic activity as well as water and nutrient uptake (Morard et al., 2000; Soffer and Burger, 1988; Sojka and Stolzy, 1980; Sojka and Stolzy, 1988). In greenhouse production, short-term oxygen deficiencies that inhibit root growth are caused by excess amounts of irrigation that occur due to current industry practices (Raviv and Lieth, 2008). The challenge for bedding plant producers is to find the balance between optimal growth and strong root development in their irrigation management program.

The objectives of this research were 1) to determine the effects of substrate water content on *Impatiens walleriana* 'Xtreme Orange' and *Catharanthus roseus* 'Pacifica Deep Orchid' in early production stages when not thoroughly watered in at potting, 2) to determine depth of rooting within the container at varying substrate water contents, and 3) determine the effects of plant growth as influenced by two irrigation regimes.

Materials and Methods

This study took place at the Paterson Greenhouse Complex on the campus of Auburn University. On 28 Jan. 2017, an 80 peat:20 perlite substrate (by vol.) was mixed using a mortar mixer (Whiteman Industries Inc., Carson, CA). The peat was sifted through a 9.525mm (3/8-inch) screen before mixing. The substrate was amended with 2.3 $kg \cdot m^{-3}$ (5 $lbs \cdot yd^{-3}$) of ground dolomitic limestone, 0.45 $kg \cdot m^{3}$(1 $lbs \cdot yd_{-3}$) of AquaGro-G® (Aquatrols, Paulsboro, NJ), 1.36 $kg \cdot m^{-3}$ (3 $lbs \cdot yd^{-3}$) of a 2-3-month Polyon® 16-6-13 fertilizer with micronutrients (16N-2.6P-10.8K, Harrell's LLC, Lakeland, FL), and 0.45 $kg \cdot m^{-3}$ (1 $lbs \cdot yd^{-3}$) of MicroMax® micronutrient package (Everris, The Netherlands). As the substrate was mixing, 200 ppm N sourced from TotalGro™ 20-10-20 (20N-4.4P-16.6K) water soluble fertilizer (SDT Industries Inc., Winnsboro, LA) was dissolved in 3.78 L of water and slowly applied by spraying directly to the substrate. Six 10.2-cm (Dillen Products, Middlefield, OH) were loosely filled to the brim with the prepared substrate and dropped five times on a table to settle the substrate 1.6 cm below the brim. The containers were then weighed, and minor adjustments were made to bring the mass of added substrate of each container to 120 g. Containers were then well watered and allowed to drain for two hours in a cool, dark room. Containers were weighed, placed in a forced air-drying oven at 60 °C for two days and weighed again to determine the amount of dry substrate per container. It was determined that the containers held 33.4 g dry substrate, and the average gravimetric water content at container capacity was 86%.

On 28 Jan. 2017, 370 10.2 cm containers were filled with 120 g of substrate and placed into six blocks upon a bench in a temperature controlled greenhouse and left to dry down for one week. Ten random empty containers were weighed to calculate an average empty container weight.

Impatiens

On 6 Feb. 2017, ten of the filled containers were watered thoroughly and allowed to drain for approximately two hours after which the Virginia Tech extraction method was used to determine initial substrate pH and electrical conductivity (EC) (Wright, 1986). *Impatiens walleriana* 'Xtreme Orange' plugs were transplanted from a 200-cell plug trays (Young's Plant Farm, Inc., Auburn, AL) one each into 180 of the filled containers. Twenty plugs were randomly pulled from the flats to determine the average fresh weight per plug (2.29 g).

After potting, each of the 180 containers was weighed to determine the volume of water needed to bring the container to a target GWC of 86%, 82%, 78%, 74%, or 70%. The weight of the container at its target GWC was calculated by dividing the dry weight of the substrate in each container by the following formula: [Dry weight of substrate/ (1-Target GWC) + avg. weight of empty container + avg. plug weight]. The volume of water needed to bring each container to its target weight was slowly distributed evenly across the substrate surface using a 60-mL syringe directly after plug transplant. Plant size was recorded weekly by measuring size indices (SI) for all plants [(height + widest width + perpendicular width) ÷ 3]. At 7 and 14 days after potting (DAP), one sample per treatment per block was irrigated with precisely enough water to bring the substrate to container capacity and left to sit on a greenhouse bench for a minimum of two hours after which water was applied by syringe to induce leaching. Substrate pH and EC were measured using the Virginia Tech extraction method (Wright, 1986). Plants were then gently removed from the containers, and roots were washed free of substrate in a water bath. Plants were then pat dried and allowed to sit on a greenhouse bench for 30-60 min to air dry. Fresh plant weight and root length were measured. Roots and shoots were separated and placed into a forced air-drying oven at 60 °C until a constant weight was reached. The average plant fresh weight per treatment was used to update the target GWC formula in place of the initial plug weight to account for increased plant mass in the formula. On 20 Feb. (14 DAP), the remaining 120 plants were brought to container capacity and reassigned to new irrigation treatments. Within each block, half of each treatment group was reassigned to a “wet” treatment while the other half was reassigned to a “wet/dry” treatment. Plants in the wet treatment were allowed to dry to 82% substrate GWC before being irrigated to container capacity. Plants in the wet/dry treatment were allowed to dry to 70% substrate GWC before being irrigated to container capacity. Plant weights were checked daily at 9:00 AM and irrigated only if substrate GWC had fallen below the target. As temperatures increased, and plants transpired more water, substrate GWC was checked twice daily at 9:00 AM and 5:00 PM. One plant per initial/second irrigation treatment combination per block was harvested 21 and 28 DAP (7 and 14 days after initiation of the second irrigation treatments). Plants were harvested in the same fashion as those harvested 7 and 14 DAP.

Annual Vinca

On 8 Feb. 2017, ten of the containers filled on 28 Jan. were watered thoroughly and allowed to drain for approximately two hours after which the Virginia Tech extraction method was used to determine initial substrate pH and electrical conductivity (EC) (Wright, 1986). *Catharanthus roseus* 'Polka Dot' plugs were transplanted from two 200-cell plug trays (Young's Plant Farm, Inc., Auburn, AL) one each into 180 of the containers filled on 28 Jan. Twenty plugs were randomly pulled from the two flats to determine the average fresh weight per plug (2.29 g).

The same procedures as those described for impatiens were carried out with some exceptions. Initial irrigation treatments were maintained for 21 days instead of 14 days. One plant per treatment per block was harvested 7, 14, and 21 DAP. On 1 Mar. (21 DAP), half of each treatment group was reassigned to the "wet" treatment while the other half was reassigned to the "wet/dry" treatment. Harvests occurred on 28, 35, 42, and 49 DAP.

An analysis of variance was performed on all responses using PROC GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a randomized complete block with experimental runs entered in the model as a random variable. The normal probability distribution was used for all responses except dry weight and root: shoot ratio where the log normal distribution was used. Each plant species was analyzed separately. The treatment design was a 3-way factorial of gravimetric water content, growing regime, and sampling week. Where residual plots and a significant covariance test indicated heterogeneous variance among treatments, a RANDOM statement with the GROUP option was used to correct heterogeneity. Differences among growing regime least squares means were determined using the simulated method. Linear and quadratic trends over gravimetric water content and sampling week were tested using model regressions. All significances were at $p \leq 0.05$.

Results

Impatiens

The initial GWC by week interaction was significant at $p \leq 0.05$ for size indices. Size indices increased linearly with increasing GWC at the $p \leq 0.01$ level at 7 DAP, and there was a quadratic response at the $p \leq 0.01$ level at 14 DAP (Table 4.1). At 21 and 28 DAP, treatments had no effect on SI.

The initial GWC by week interaction was significant at $p \leq 0.05$ for height. Height was not significant at 7 or 28 DAP (Table 4.2). At 14 and 21 DAP, there was a quadratic response between target GWC and height at the $p \leq 0.05$ level. The mean height of impatiens in the 70% dry treatment was 8.4 inches while the mean height of impatiens in the 100% dry treatment was 6.9 inches. There was no significant difference for plants among the remaining treatments. The mean height 14 DAP ranged from 9.4 cm for plants in the 70% GWC treatment before increasing slightly to 11.2 cm for plants in the 100% GWC treatment while the mean height 21 DAP ranged from 16.3 cm for plants in the 70% treatment before decreasing to 15.0 cm for the plants in the 86% GWC treatment.

The initial GWC by week and wet/dry interactions were significant at $p \leq 0.05$ for pH. Substrate pH at 7 DAP was linear at the $p \leq 0.01$ level. Substrate pH ranged from 4.72 at the 70% level to 5.03 at the 86% level (Table 4.3). At 14 DAP, a quadratic response was detected at the $p \leq 0.01$ level. Substrate pH ranged from 4.97 at the 70% level to 5.4 at the 86% level. No significant difference was detected for pH at the 21 DAP mark. A linear response at the $p \leq 0.05$ level was detected for pH at 28 DAP. Substrate pH ranged from 4.97 at the 70% level before decreasing to 4.90 at the 78% level before increasing again to 5.10 at the 86% level.

The week by wet/dry interactions were significant at $p \leq 0.05$ for pH. No significant difference was detected between the wet/dry treatments for pH at 7 and 14 DAP (Table 4.4). At 21 DAP, a significant difference was detected between the wet/dry treatments. The pH for the wet/dry cycle treatment was 5.39 compared to 5.22 for the consistently wet treatment. A significant difference was detected for pH at 28 DAP. In the 70% GWC treatment, pH was 5.12 while pH in the 86% treatment was 4.80.

The GWC and wet/dry main effects were significant at $p \leq 0.05$ for EC. EC ($mS \cdot cm^{-1}$) produced a linear response at the $p < 0.001$ level (Table 4.5). EC ranged from 3.22 $mS \cdot cm^{-1}$ in the wet/dry cycle to 2.41 in the consistently wet treatment.

The GWC by week interaction was significant at $p \leq 0.05$ for shoot dry weight (SDW) (Table 4.6). No significant difference was detected at seven days. A linear response at the $p \leq 0.05$ level at 14 DAP. SDW ranged from 0.18 g at the 70% level to 0.23 g at the 100% level. A quadratic response at the 0.05 level was detected at twenty-one days. SDW ranged from 0.50 g at the 70% level to 0.61 g at the 100% level. At 28 DAP, a quadratic response was detected at the $p \leq 0.01$ level. Means ranged from 1.17 g at the 70% level to 1.34 g at the 82% level before slightly decreasing to 1.33 g at the 86% level.

The GWC by week interaction was significant at $p \leq 0.05$ for root:shoot ratio (Table 4.7). A linear response at the $p \leq 0.001$ level was detected at 7 DAP. Root:shoot ratio ranged from

2.96 at the 70% level to 2.44 at the 86% level. A quadratic response was detected at the 0.001 level at 14 DAP. The root:shoot ratio was maximum at the 70% level at 2.17 before steadily decreasing down to 1.02 at the 86% level. No significant difference was detected at 21 and 28 DAP.

Annual Vinca

The initial GWC by week interaction was significant at $p \leq 0.05$ for size index (Table 4.8). No significant difference was detected at 7 or 14 DAP. At twenty-one days, a linear response at the $p \leq 0.01$ level was detected. The mean size index ranged from 6.3 in at the 70% level and increased steadily to 7.4 in. at the 86% level. No significant difference was detected at 28, 35 and 42 DAP. At 49 DAP, a quadratic response at the 0.001 level was detected. The means ranged from 13.89 at the 70% level to 11.71 at the 86% level.

The initial GWC by week interactions were significant at $p \leq 0.05$ for pH. A linear response at the $p \leq 0.001$ level was detected at 7 DAP (Table 4.9). Substrate pH ranged from 5.14 at the 70% level to 5.32 at the 86% level. At 14 and 21 DAP, a quadratic response at the $p \leq 0.05$ level was detected. Mean pH ranged from 5.13 to 5.39 at the 70% and 86% level respectively for 14 DAP and 5.19 to 5.59 at the 70% and 86% level respectively at twenty-one days. No significant difference for pH was detected at 28 DAP. At 35 and 42 DAP, a linear response at the $p \leq 0.001$ level was detected. Means ranged from 5.38 to 5.65 at 35 DAP and 5.4 to 5.6 at 42 DAP at the 70% and 86% levels respectively. At 49 DAP, a linear response at the $p \leq 0.05$ level was detected. Means ranged from 5.45 to 5.61 at the 70% and 86% levels.

The wet/dry treatment by week interactions were significant at $p \leq 0.05$ for pH. No significant difference was detected between the wet/dry treatments for pH at 7, 14, 21, 28, 35, and 42 DAP (Table 4.10). At 49 DAP, a significant difference was detected between pH and wet/dry treatments. Substrate pH for the wet/dry cycle treatment was 5.6 compared to 5.4 for the consistently wet treatment.

The initial GWC by week interactions were significant at $p \leq 0.05$ for EC ($mS \cdot cm^{-1}$). At 7, 14 and 21 DAP, a linear response at the $p \leq 0.001$ level was detected (Table 4.11). The mean EC ranged from 4.70 $mS \cdot cm^{-1}$ to 3.71 $mS \cdot cm^{-1}$ at 7 DAP and 4.36 $mS \cdot cm^{-1}$ to 3.37 $mS \cdot cm^{-1}$ at 14 DAP, and 5.37 $mS \cdot cm^{-1}$ to 2.95 $mS \cdot cm^{-1}$ at 21 DAP. A linear response at the $p \leq 0.01$ level was detected at 28 DAP. The mean EC ranged from 5.89 $mS \cdot cm^{-1}$ to 3.36 $mS \cdot cm^{-1}$. At 35 and 42 DAP, a linear response at the $p \leq 0.001$ level was detected. Mean EC ranged from 3.66 $mS \cdot cm^{-1}$ to 2.23 $mS \cdot cm^{-1}$ for 35 DAP, and 3.59 $mS \cdot cm^{-1}$ to 2.59 $mS \cdot cm^{-1}$ for 42 DAP. EC decreased linearly with increasing GWC at the 0.01 level 49 DAP Mean EC ranged from 2.65 $mS \cdot cm^{-1}$ to 1.50 $mS \cdot cm^{-1}$.

The wet/dry treatment by week interactions for EC ($mS \cdot cm^{-1}$) were significant at $p \leq 0.05$. No significant difference was detected between the wet/dry treatments at 7, 14, 21, 28 and 35 DAP Table 4.12). At 42 DAP, a significant difference was detected between the wet/dry treatments for EC. EC for the wet/dry cycle treatment were 2.97 $mS \cdot cm^{-1}$ compared to 3.36 $mS \cdot cm^{-1}$ for the consistently wet treatment. At 49 DAP, a significant difference was detected between wet/dry treatments for EC. EC for the wet/dry cycle treatment were 1.84 $mS \cdot cm^{-1}$ while EC's for the wet treatment were 2.47 $mS \cdot cm^{-1}$.

The initial GWC by week interaction was significant at $p \leq 0.05$ for shoot dry weight (SDW) (Table 4.13). No significant difference for SDW was detected at 7, 14, 21 and 28 DAP. At 35 and 42 DAP, SDW increased linearly with increasing GWC. The mean SDW ranged from 0.64 g to 0.91 g at thirty-five DAP and 0.78 g to 0.98 g at forty-two DAP. A quadratic response was detected at the $p \leq 0.001$ level for SDW at 49 DAP. The mean SDW ranged from 1.58 g for the plants in the 70% treatment to 0.74g for plants in the 82% treatment before increasing to 1.32 g for plants in the 100% treatment.

The initial GWC by week interaction was significant at $p \leq 0.05$ for root dry weight (RDW). No significant difference for RDW was detected at 7, 14, 21, 28, 35, or 42 DAP (Table 4.14). At 49 DAP, a quadratic response at the $p \leq 0.001$ level was detected. The mean RDW ranged from 0.38 g in the 70% treatment to 0.08 g in the 82% treatment and increasing to 0.20 g in the 100% treatment.

The initial GWC by week interaction was significant at $p \leq 0.05$ for root:shoot ratio. At 7 DAP, root:shoot ratio decreased linearly with increasing GWC (Table 4.15). The mean ratio ranged from 0.30 for the 70% treatment to 0.17 for the 100% treatment. A quadratic response was detected at the 0.001 level for root: shoot ratio at 14 DAP. The mean ratios ranged from 0.46 for the 70% treatment to 0.14 for the 100% treatment. At 21 DAP, root:shoot ratios decreased linearly with increasing GWC.. Mean ratios ranged from 0.32 to 0.15 for the 70% and 100% treatments respectively. No significant difference was detected for root: shoot ratio at 28 DAP. At 35,42, and 49 DAP, root:shoot ratio decreased linearly with increasing GWC. Mean ratios ranged from 0.29 to 0.16 at 35 DAP, 0.23 to 0.12 at 42 DAP, and 0.33 to 0.21 at 49 DAP for the 70% and 86% treatments, respectively.

Conclusion

At 28 DAP, no significant difference was detected for height and SI for impatiens. We can conclude that maintaining low substrate water contents for the first two weeks had no detrimental effects on long-term growth of impatiens. At 49 DAP for annual vinca, a quadratic response was detected between initial GWC and both SDW and SI. Annual vinca grown in 70% substrate GWC during the first two weeks and subsequently exposed to a wet/dry cycle afterwards were larger than those plants grown in 86% substrate GWC and being sustained at that level over the course of the experiment.

We can conclude that growing annual vinca at drier substrate moisture contents has no detrimental effects on long-term growth. Our study differs from research conducted by others which concluded that as substrate water content decreased, plant biomass decreased accordingly (Burnett and van Iersel, 2008; Khalil et al., 2008; Kim and van Iersel, 2009; van Iersel and Nemali, 2004; Zhen and Burnett, 2015). Our study showed that as substrate water content maintained during the first two weeks decreased, size indices of *Catharanthus roseus* increased. This may be in part to vinca requiring mixes of higher porosities than other commonly grown bedding plants (Thomas, 2012).

Literature Cited

Burnett, S.E. and M.W. van Iersel. 2008. Morphology and irrigation efficiency of *Guara lindheimeri* grown with capacitance sensor-controlled irrigation. HortScience 43:1555-1560.

Cai, X., and T. Starman. 2014. The effect of substrate moisture content on growth and physiological responses of two landscape roses (*Rosa hybrida* L.). HortScience 49: 741-745.

Kim, J., and M.W. van Iersel. 2009. Daily water use of abutilon and lantana at various substrate water contents. Proc. Southern Nurs. Assn. Res. Conf. 54:12-16.

Khalil, S.K., R. St. Hilaire, M. O'Connell and J. Mexal. 2008. Growth of moonshine yarrow on a limited moisture budget. J. Environ. Hort. 26:70-74.

Kozlowski, T.T. and S.G. Pallardy. 2002. Acclimation and adaptive responses of woody plants to environmental stresses. Botanical Rev. 68:270-334.

Lea-Cox, John. 2016. When exactly should I irrigate? Greenhouse Product News, Sparta, MI. 13 April 2018. <https://gpnmag.com/article/when-exactly-should-i-irrigate/>

Morard, P., L. Lacoste, and J. Silvestre. 2000. Effect of oxygen deficiency on uptake of water and mineral nutrients by tomato plants in soilless culture. J. of Plant Nutr. 23:1063-1078.

Raviv, M. and J.H. Lieth. 2008. Soilless culture: Theory and Practice. Elsevier. Burlington, MA.

Soffer, H. and D.W. Burger. 1988. Effects of dissolved oxygen concentrations in aero-hydroponics on the formation and growth of adventitious roots. J. Amer. Soc. Hort. Sci. 113:218-221.

Sojka, R.E. and L.H. Stolzy. 1980. Soil-oxygen effects on stomatal response. Soil Sci. 30:350-358.

Sojka R.E. and L.H. Stolzy. 1988. Mineral nutrition of oxygen-stressed crops and its relationship to some physiological responses. p.429-440. In: D.D. Hook (ed.). The ecology and management of wetlands. Vol. 1. Croom Helm, Beckenham, UK.

Thomas, P., J.F. Woodward, F. Stegelin, and B. Pennisi. 2012. A guide for commercial production of vinca. Univ. of Georgia Coop. Ext., Bul. 1.

van Iersel, M. W. and K.S. Nemali. 2004. Drought stress can produce small but not compact marigolds. HortScience 39:1298-1301.

van Iersel, M.W., S. Dove, J. Kang, and S.E. Burnett. 2010. Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience 45:277-282.

Wright, R.D. 1986. The pour-thru nutrient extraction procedure. HortScience 21:227-229.

Table 4.1. Size indices of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target	Size Index[z]				
GWC[y]	7 DAP[x]	14 DAP	21 DAP	28 DAP	Significance[w]
70%	4.30	6.40	10.80	14.50	Q***
74%	4.60	6.60	10.80	14.30	Q***
78%	4.40	7.00	10.80	14.00	Q***
82%	4.60	7.10	10.90	14.60	Q***
86%	4.60	7.30	11.00	13.90	Q**
Significance[v]	L**	Q**	NS	NS	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.05$(*) or 0.001 (***). NS= not significant.

[v] Significant linear or quadratic trends for GWC using model regression at $P < 0.01$(**), or 0.001 (***). NS= not significant.

Table 4.2. Height of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	Height (in)[z]				Significance[w]
	7 DAP[x]	14 DAP	21 DAP	28 DAP	
70%	2.70	3.70	6.40	8.20	Q***
74%	3.00	4.00	6.10	7.50	Q**
78%	2.80	4.20	5.90	7.40	L***
82%	2.80	4.30	5.90	7.80	L***
86%	2.80	4.40	5.90	7.40	L***
Significance[v]	NS	Q*	Q*	NS	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.
[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.
[x] Days after Potting.
[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.01$ (**) or 0.001 (***).
[v]Significant linear or quadratic trends for GWC using model regression at $P < 0.05$(*). NS= not significant.

Table 4.3. Substrate pH of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	pH				
	7 DAP[x]	14 DAP	21 DAP	28 DAP	Significance[w]
70%	4.72	4.97	5.43	4.97	Q***
74%	4.78	5.09	5.20	4.90	Q***
78%	4.81	5.20	5.27	4.90	Q***
82%	4.94	5.34	5.30	4.92	Q***
86%	5.03	5.41	5.33	5.10	Q***
Significance[v]	L**	Q***	NS	L*	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w]Significant (Sign.) linear or quadratic trends using model regression at $P < 0.01$ (**) or 0.001 (***). NS= not significant.

[v] Significant linear or quadratic trends for GWC using model regression at $P < 0.05$(*), 0.01 (**) or 0.001 (***). NS= not significant.

Table 4.4. Substrate pH of *Impatiens walleriana* (Hook.f) 'Pacifica Deep Orchid' as affected by simulated wet/dry (WD) cycle in two experimental runs[z].

Final Irrigation Treatments[y]	pH				Significance[w]
	7 DAP[x]	14 DAP	21 DAP	28 DAP	
Wet/dry Cycle	4.86ns	5.19ns	5.39a	5.12a	L***
Consistently Wet	4.85	5.2	5.22b	4.80b	Q**

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.
[y]Irrigation treatments applied from 14 to 28 DAP. Wet/dry cycle treatment allowed to dry to 70% GWC before being irrigated to container capacity. Consistently wet treatment allowed to dry to 82% GWC before being irrigated to container capacity.
[x]Days after Potting.

[w]Least squares means comparisons between WD for each week using the simulated method at $P < 0.05$. NS= not significant.

Table 4.5. Electrical Conductivity (EC) of *Impatiens* ×*walleriana* 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	EC ($mS\cdot cm^{-1}$)
70%	3.22
74%	3.54
78%	3.11
82%	2.71
100%	2.41
Significance[x]	L***

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.
[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.
[x]Significant linear trends using model regression at $P < 0.001$ (***).

Table 4.6. Shoot Dry Weight of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target	Shoot Dry Weight				
GWC[y]	7 DAP[x]	14 DAP	21 DAP	28 DAP	Significance[w]
70%	0.06	0.18	0.50	1.17	Q***
74%	0.05	0.18	0.54	1.28	Q***
78%	0.09	0.22	0.58	1.28	Q***
82%	0.06	0.23	0.59	1.34	Q***
86%	0.06	0.23	0.61	1.33	Q***
Significance[v]	NS	L*	Q*	Q***	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.
[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.
[x]Days after Potting.
[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.001$ (***).
[v]Significant linear or quadratic trends for GWC using model regression at $P < 0.05$ (*) or 0.001 (***). NS= not significant.

Table 4.7. Root:Shoot ratio of *Impatiens walleriana* (Hook.f) 'Xtreme Orange' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	Root:Shoot ratio 7 DAP[x]	14 DAP	21 DAP	28 DAP	Significance[w]
70%	2.96	2.17	1.08	0.60	L***
74%	3.66	1.9	0.94	0.66	Q***
78%	2.8	1.27	0.82	0.69	Q***
82%	2.38	1.05	0.85	0.50	Q**
86%	2.44	1.02	0.74	0.59	Q***
Significance[v]	L***	Q***	NS	NS	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.01$ (**) or 0.001 (***).

[v]Significant linear or quadratic trends for GWC using model regression at $P < 0.001$ (***). NS= not significant.

Table 4.8. Size Indicies of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) in two experimental runs[z].

	Size Index							
Initial Target GWC[y]	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
70%	4.82	5.47	6.27	6.54	9.78	10.24	13.89	Q***
74%	4.88	5.65	6.78	7.21	9.45	10.06	13.32	Q***
78%	5.00	5.59	6.89	7.18	9.46	9.70	10.69	L***
82%	4.81	5.58	7.19	7.09	9.52	10.09	8.99	Q***
86%	4.96	5.64	7.43	7.24	10.07	10.46	11.71	L***
Significance[v]	NS	NS	L**	NS	NS	NS	Q***	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x]Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.001$ (***).

[v]Significant linear or quadratic trends for GWC using model regression at $P < 0.01$(**), or 0.001 (***). NS= not significant.

Table 4.9. Substrate pH of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	pH							Significance[w]
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	
70%	5.14	5.13	5.19	5.27	5.38	5.4	5.45	L***
74%	5.14	5.20	5.26	5.27	5.35	5.37	5.57	L***
78%	5.21	5.27	5.37	5.35	5.46	5.45	5.50	L***
82%	5.21	5.29	5.47	5.36	5.51	5.48	5.57	Q*
86%	5.32	5.39	5.59	5.36	5.65	5.56	5.61	Q**
Significance[v]	L***	Q*	Q*	NS	L***	L***	L*	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at P < 0.05(*), 0.01 (**) or 0.001 (***).

[v] Significant linear or quadratic trends for GWC using model regression at P < 0.01(**) or 0.001 (***). NS= not significant.

Table 4.10. Substrate pH of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by simulated wet/dry (WD) cycle in two experimental runs[z].

Final Irrigation Treatments[y]	pH							
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
Wet/dry cycle	5.20ns	5.26ns	5.38ns	5.32ns	5.46ns	5.47ns	5.64a	L***
Consistently wet	5.20	5.26	5.37	5.32	5.48	5.44	5.44b	Q**

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Irrigation treatments applied from 21 to 49 DAP. Wet/dry cycle treatment allowed to dry to 70% GWC before being irrigated to container capacity. Consistently wet treatment allowed to dry to 82% GWC before being irrigated to container capacity.

[x] Days after Potting.

[w]Least squares means comparisons between WD for each week using the simulated method at $P < 0.05$. NS= not significant.

Table 4.11. Electrical Conductivity (EC) of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	EC (mS·cm^{-1})							
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
70%	4.30	4.31	4.97	4.28	3.55	3.36	2.33	Q***
74%	4.70	4.36	5.37	5.89	3.66	3.59	2.00	Q***
78%	4.24	3.69	4.30	4.38	3.30	3.24	2.65	L***
82%	4.30	4.03	3.85	4.25	2.91	3.03	2.31	L***
86%	3.71	3.37	2.95	3.36	2.23	2.59	1.50	L***
Significance[v]	L***	L***	L***	L**	L***	L***	L**	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w]Significant linear or quadratic trends using model regression at $P < 0.001$ (***).

[v] Significant linear or quadratic trends for GWC using model regression at $P < 0.01$(**), or 0.001 (***). NS= not significant.

Table 4.12. Electrical Conductivity of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by simulated wet/dry (WD) cycle in two experimental runs[z].

Final Irrigation Treatments[y]	EC($mS\cdot cm^{-1}$)							
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
Wet/dry cycle	4.25ns	3.95ns	4.28ns	4.43ns	3.13ns	2.97b	1.84b	Q***
Consistently wet	4.25	3.95	4.29	4.43	3.14	3.36a	2.47a	Q**

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Irrigation treatments applied from 21 to 49 DAP. Wet/dry cycle treatment allowed to dry to 70% GWC before being irrigated to container capacity. Consistently wet treatment allowed to dry to 82% GWC before being irrigated to container capacity.

[x] Days after Potting.

[w]Least squares means comparisons between WD for each week using the simulated method at $P < 0.05$. NS= not significant.

Table 4.13. Shoot Dry Weight of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target	Shoot Dry Weight							
GWC[y]	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
70%	0.08	0.1	0.19	0.36	0.64	0.78	1.58	Q***
74%	0.08	0.1	0.22	0.39	0.74	0.83	1.54	Q***
78%	0.09	0.11	0.25	0.41	0.83	0.84	1.02	L***
82%	0.08	0.11	0.29	0.44	0.84	0.89	0.74	L***
86%	0.08	0.12	0.29	0.44	0.91	0.98	1.32	Q**
Significance[v]	NS	NS	NS	NS	L**	L**	Q***	

[z] First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y] Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x] Days after Potting.

[w] Significant linear or quadratic trends for DAP using model regression at P < 0.01(**) or 0.001 (***).

[v] Significant linear or quadratic trends for GWC using model regression at P < 0.01(**) or 0.001 (***). NS= not significant.

Table 4.14. Root Dry Weight of *Catharathus roseus* (L.) 'Pacifica Deep Orchid' as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	Root Dry Weight							
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
70%	0.02	0.04	0.06	0.07	0.15	0.15	0.38	Q***
74%	0.02	0.04	0.06	0.07	0.16	0.16	0.39	Q***
78%	0.02	0.03	0.05	0.07	0.16	0.16	0.19	L***
82%	0.01	0.02	0.05	0.07	0.14	0.14	0.08	L***
86%	0.01	0.02	0.04	0.07	0.13	0.13	0.20	L***
Significance[v]	NS	NS	NS	NS	NS	NS	Q***	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x]Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.001$ (***).

[v] Significant linear or quadratic trends for GWC using model regression at $P < 0.001$ (***). NS= not significant.

Table 4.15. Root: Shoot Ratio of *Catharathus roseus* 'Pacifica Deep Orchid' (L.) as affected by target gravimetric water content (GWC) in two experimental runs[z].

Initial Target GWC[y]	Root: Shoot Ratio							
	7 DAP[x]	14 DAP	21 DAP	28 DAP	35 DAP	42 DAP	49 DAP	Significance[w]
70%	0.30	0.46	0.32	0.24	0.29	0.23	0.33	L*
74%	0.36	0.42	0.31	0.21	0.24	0.2	0.34	Q*
78%	0.31	0.27	0.24	0.21	0.20	0.18	0.25	L**
82%	0.15	0.17	0.20	0.19	0.17	0.14	0.17	NS
86%	0.17	0.14	0.15	0.19	0.16	0.12	0.21	NS
Significance[v]	L***	Q***	L***	NS	L*	L*	L*	

[z]First experimental run ran from 8 Feb. to 21 Mar. 2017. Second experimental run ran from 2 Mar. to 19 Apr. 2017.

[y]Maintained at these GWC for first 14 DAP before implementation of simulated wet/dry cycle.

[x]Days after Potting.

[w]Significant linear or quadratic trends for DAP using model regression at $P < 0.05$ (*) or 0.01 (**). NS= not significant.

[v]Significant linear or quadratic trends for GWC using model regression at $P < 0.05$ (*) or 0.001 (***). NS= not significant.

Chapter 5

Conclusion

In these studies, gravimetric water content and substrates with an increased water holding capacity have been shown to be a management practice that can decrease water demand for the first two weeks of greenhouse production. More importantly, Chapter 4 shows that withholding water during the first two weeks of production before switching to a more intensive irrigation strategy produced more dry matter than those plants kept in an intensive irrigation regime throughout the course of the experiment.

In Chapter 2, we found that maintaining low substrate moisture contents directly after transplanting resulted in significantly smaller impatiens as soon as 2 WAP. Lower substrate water contents did not result in a higher percentage of total root growth in the bottom half of the container.

In Chapter 3, diminishing returns were observed both for shoot and root weight between the 80% and 82% treatment levels. Shoot weight increased 29% between 80% and 82% while total root dry weight increased 64% between these two treatments. We can conclude that target GWC when maintained between 80% and 82% had no effect on depth of root growth during the first three weeks of impatiens production. We can conclude that target GWC had no effect on annual vinca size over the course of the five-week experimental run.

In Chapter 4, plants kept in the drier regime produced larger and taller overall plants at study termination compared to those kept at container capacity daily. For *Catharanthus roseus*

(L.), plants kept in the drier regimes produced more shoot and root biomatter compared to those in the higher irrigation regime treatments.

Further research must continue to be done in irrigation management practices in nursery and greenhouse production. Future demands on fresh water resources may lead to reductions in the agricultural sector for irrigation water. The studies presented here indicate further studies should be conducted to improve efficiency. Further study needs to be conducted on more bedding plant species. Varying plant families and species within have varying optimal growth conditions when compared to those presented here.

Further study also needs to be conducted utilizing automated systems to manage the substrate moisture contents. Growers don’t irrigate individual crops by hand so further study needs to look at how large-scale irrigation systems can effectively irrigate crops in a production setting utilizing soil moisture sensors to monitor substrate moisture contents.