IRRIGATION, FERTILIZATION AND NON-CHEMICAL PLANT GROWTH REGULATION IN GREENHOUSE PRODUCTION

by

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(UNDER THE DIRECTION OF MARC VAN IERSEL AND PAUL THOMAS)

ABSTRACT

Greenhouse crop production depends on regular applications of water and fertilizer. Intensive and often excessive water and fertilizer applications are common in greenhouse. Excess water and fertilizer use result in leaching, runoff, and environmental degradation. Fertilizer costs are increasing and water scarcity is well documented. Hence, there is need for improvement in water and fertilizer use efficiency. We conducted an experiment to determine if less water and lower fertilizer concentrations can be used to grow bedding plants in a greenhouse when plants are watered efficiently. We grew petunia (*Petunia ×hybrida* 'Dreams White') at four levels of substrate water content (θ) (0.1, 0.2, 0.3, and 0.4 $m^3 \cdot m^{-3}$) with eight rates of controlled release fertilizer (0 to 2.5 g/plant). Plant water use increased with increasing θ threshold. Flowering reduced with increasing θ and fertilizer rate. We also conducted an experiment to determine feasibility of using controlled water deficit (WD) to regulate plant height of poinsettia (*Euphorbia pulcherrima*) 'Classic Red'. Poinsettias were grown from rooted stem cutting and exposed to WD or plant growth regulators (PGR) to control stem elongation. Regulated water deficit resulted in an average height of 44.5 cm, closest to the target height (43.5 cm). However, there are limits on how much height control can be achieved through WD. For 'Classic Red', a high vigor cultivar, the lowest height limit achievable with WD is 39-40 cm. Application of long durations of WD reduced bract area.

To understand how irrigation regimes and fertilizer concentrations affect leaching and growth of bedding plants, petunias were grown with two fertilizer concentrations (100 and 200 mg·L^{-1} N) and four irrigation volumes, control (minimal leaching), low, medium and high. The higher fertilizer concentration (200 vs. 100 mg·L^{-1} N) resulted in larger plants, regardless of irrigation and leaching volumes. The larger plants had greater water use and thus needed more frequent irrigation to replenish the used water. Both large irrigation volumes and more frequent irrigation increases leaching if θ is close to container capacity. More efficient irrigation reduced the amount of water, and thus water-soluble fertilizer, that was applied.

INDEX WORDS: Ageratum, daily light integral, dianthus, efficient irrigation, impatiens, leaching, petunia, plant growth regulators, poinsettias, soil moisture sensors, vapor pressure deficit, water deficit.

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DEDICATION

I dedicate this dissertation to the memory of my mother (Akumu Alem) and father (Yonah Alem) and the humble life they led. They never went to school, lived and died in a small village in Kenya and they had unconditional love for us.

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CHAPTER 1

INTRODUCTION

Continued supply of good quality water is critical for productivity in protected production systems, such as greenhouses, that rely heavily on irrigation (Taylor et al., 2006; Saha et al., 2008). Controlled environment production systems involve careful control of plant nutrition and irrigation to ensure good quality crops. Approximately 40% of world food is produced using irrigation (FAO, 2002; Mao et al., 2003) and irrigation consumes about 70% of the world fresh water resources (Fry, 2005; Fischer et al., 2007; Pardossi et al., 2009). Plant production is limited in many parts of the world by availability of fresh water suitable for irrigation (Falkenmark, 1997; Rockstrom, 2007; Fernández et al., 2009). With increasing world population (Rosen, 2000; Hightower and Pierce, 2008), urbanization, industrialization and climate change, fresh water is increasingly becoming scarce around the world (Petit et al., 1999). There is a need for crop producers using both field and sheltered production systems to adopt sustainable irrigation methods and water management practices.

Greenhouse production is one of the most important sheltered production systems for supply of vegetables, fruits, and ornamental plants. Greenhouse production is an intensive farming method that involves heavy fertilizer and irrigation water use (Ling, 2004). Greenhouse production systems are also one of the highest energy consuming crop production systems. A lot of energy is usually used to maintain optimal environmental conditions for plant growth, fertilization and irrigation (Canakci and Akinci, 2006). Due to its dependence on irrigation, greenhouse production is highly susceptible to effects of currently increasing water scarcity and decreasing water quality (Lea-Cox and Ross, 2001), which may lower profit margins (Nelson, 1990) due to poor quality crops and increased cost of irrigation. Thus, efficient water and nutrient management is critical for continued sustainability and profitability of greenhouse production (Jovicich et al., 2007). Using efficient irrigation methods that reduce or eliminate leaching can reduce water wastage, and reduce costs of greenhouse production (Barrett, 1991; Million et al., 2007; Majsztrik et al., 2011). In many parts of the United States, greenhouse growers have to deal with nutrient-loaded runoff resulting from less efficient irrigation methods such as overhead (Weatherspoon and Harrell, 1980). Leaching in greenhouse production is further encouraged by excessive fertilizer application (Chen and Caldwell, 2001). The future of irrigation in greenhouses will need to include techniques that limit leaching and enhance efficient water use in container plant production (Warsaw et al., 2009).

Leachate from greenhouse facilities may not only carry nutrients into the environment, but can also contain other agrochemicals. Growers are also facing pressure to reduce use of agrochemicals in plant production. Among chemicals leached from greenhouse facilities are pesticides and plant growth regulators (PGR) used for plant growth regulation. The use of PGRs is already facing restrictions in some countries and consumers also prefer agrochemical free plants (Clifford et al., 2004; Li et al, 2000). However, they seem indispensable in production of ornamental plants, such as poinsettia (*Euphorbia pulcherrima*). There is a current and future need to reduce of replace these chemical in plant production.

This dissertation contains studies that investigated the effect of substrate volumetric water content and fertilizer rates on water use and growth of petunia. The substrate water content at which plants are grown and the irrigation volume affect the likelihood of leaching occurrence. Different irrigation and fertilization regimes common in commercial greenhouses and relate that to leaching were simulated. A study was also conducted on regulation of plant height for compactness and quality through controlled deficit irrigation. Commercially, plant height regulation involves extensive use of plant growth regulators (PGR). Plant growth regulators are expensive and can also cause environmental pollution (Rajapakse, and Kelly, 1992). Controlled deficit irrigation can be an alternative cheap and safe technique of plant height control.

General Objectives

The objectives of the research were to 1) determine how water use and growth of *Petunia ×hybrida* are influenced by substrate volumetric water content and fertilizer rates; 2) quantify the effect of irrigation volume and fertilizer concentration on leaching and growth of *Petunia ×hybrida* under different irrigation approaches; 3) Model plant water use as function of crop light interception and other environmental measurements such as temperature, vapor pressure deficit (VPD), and relative humidity. This was done in attempt to address the current problem of irrigation scheduling in commercial greenhouses and nurseries; 4) Explore controlled deficit irrigation as an alternatives to plant growth regulators (PGRs) for plant height regulation.

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CHAPTER 2

LITERATURE REVIEW

Irrigation and leaching dynamics in greenhouse production

Greenhouse crop production is intensive and involves heavy use of fertilizer and irrigation to sustain a high plant density, as well as ensure high yields (Lea-Cox and Ross, 2001). Greenhouse yields are many times higher than field production due to near-optimal conditions and high inputs (Jensen, 2002). However, there are many challenges in greenhouse production compared to field production. Greenhouse crops are normally grown in containers with small volumes of porous soilless substrate that are likely to saturate and leach easily (Raviv et al., 1999; Chen et al., 2001; Ristvey et al., 2001). Most soilless substrates also have low cation exchange capacity (CEC) and hence are not capable of buffering nutrient availability (Rippy and Nelson, 2007). Leaching is further encouraged by excessive irrigation and fertilization prevalent in greenhouse production (Broschat, 1995; Ku and Hershey, 1997; Tyler et al., 1996).

Leaching has been ignored for many years both in traditional agriculture and horticultural industry (Sonneveld and Voogt, 2009). However, in recent years there has been a rise in concern about non-point environmental pollution caused by agricultural practices (Carpenter et al., 1998). There has been concern about excessive fertilizer and agro-chemical use, leaching, and runoff from crop production, with those fertilizers and agrochemicals ending up in groundwater or surface water and potentially causing eutrophication (Smith et al., 1999;

Berghage et al., 1999; Juntunen et al., 2003; Biernbaum, 1992; Briggs et al., 2002; Camper et al., 1994). Growers in both the greenhouse and nursery industries are increasingly concerned about the potential costs and penalties that can be incurred as result of inefficient irrigation and runoff (Yeager et al., 1997). In the United States, Maryland is one state where there are laws for phosphorous and nitrogen management in agricultural production, including greenhouse and nursery production systems (Lea-Cox et al., 2004). Florida is another state with regulations governing agricultural water use (Beeson and Brooks, 2008). While such laws may not currently exist in all states, they are expected to expand to other states, regions, and countries as water becomes scarcer and more people become interested in agricultural sustainability (Dennis et al., 2010; Fernandez et al., 2009; Wilson and Albano, 2011).

Greenhouse production can be more sustainable and less costly if limited or zero-leaching irrigation is practiced (van Iersel et al., 2010). Studies have reported that up to 65% of P or N nutrients applied in container production are lost through leaching (Dumroese et al., 1995; Juntenen et al., 2002). Growers need to adopt more efficient irrigation techniques and use research-based techniques to produce plants (Knox et al., 2012). Precision irrigation is an important component of reducing leaching and moving towards more sustainable production system (Cardenas-Lailhacar and Dukes, 2010; McCready et al., 2009; Miralles-Crespo and van Iersel, 2011). Soil moisture sensor controlled irrigation systems are an example of irrigation systems that can eliminate or limit leaching and improve water use efficiency (Nemali and van Iersel, 2008; van Iersel et al., 2009). This system can automatically maintain sufficient plant available water without leaching (Nemali and van Iersel, 2006; Burnett and van Iersel, 2008). Minimal leaching not only can save water, but also can help in production of better quality plants (Burnett and van Iersel, 2008; Uva et al., 1998). However, growers have been slow at adopting precision irrigation techniques (Chappell et al., 2013). Implementation of precision irrigation has been difficult due to variability in plant water requirements depending on species and stage of growth. Greenhouse production systems are also non-homogeneous; different plant species are often grown side by side in different container size which makes automated precision irrigation challenging (Ross et al, 2001).

Soil moisture sensors controlled irrigation system

Efficient irrigation requires constant monitoring of substrate water content to make accurate irrigation scheduling (Zhu et al., 2005). Efficient irrigation regimes should avoid or minimize leaching while at the same time supply sufficient plant available water. Current irrigation scheduling practices are based on past experiences (Greenwood et al., 2010) and human judgment, which often leaves room for human errors in irrigation scheduling. While this practice remains the most popular method of irrigation scheduling, it is costly in terms of labor and time as well as being inefficient (Lichtenberg et al., 2013). Efficient irrigation techniques should automatically monitor substrate water content and control irrigation based on real-time data of plant, soil and environmental factors (Nemali et al., 2007; Lichtenberg et al., 2013). This can save time and labor cost as well as fertilizer loss due to leaching as a result of over irrigation (Nemali and van Iersel, 2006; Testezlaf et al., 1997).

Soil moisture sensor controlled irrigation offers a viable solution for reducing leaching and runoff in greenhouse and nursery production. Soil moisture sensors inserted in the root-zone can accurately monitor soil volumetric moisture content (Nemali and van Iersel, 2006;

Bandaranayake et al., 2007; Majsztrik et al., 2011) and automatically trigger irrigation to replenish water lost due through evapotranspiration (van Iersel et al., 2011). Some soil moisture sensors such as GS-3 and 5TE (Decagon Devices Inc., Pullman, WA) can also measure substrate electrical conductivity (EC) and thus have the potential to be used in systems that monitor or control both irrigation and fertilization. Accurate EC measurements can be used to schedule fertilizer application to limit fertilizer wastage and save on cost of fertilizer (Crespo and van Iersel, 2010).

There are different types of soil moisture sensors that can be used to monitor root zone substrate water content as well as automate irrigation. Sensor such as tensiometers (Van Der Veken et al., 1982), neutron probes (Gear et al., 1977; McFall, 1978), and time domain reflectometry (TDR) probes (Ledieu et al., 1986) have been in use for a long time. However, many of these earlier sensors are not designed for container production or soilless substrate. Tensiometers for example, may not be applicable in soilless substrate due to poor contact with the substrate (Zazueta et al., 1994). They are also fragile and may cavitate in dry substrate (Pardossi et al., 2009). Some of these earlier sensors, like neutron probes, are also too big and not applicable in greenhouse production where small containers are used. The sensors are also expensive and require technical training to operate (neutron and TDR probes). Presently, there are less expensive and simpler soil moisture sensors that can be used in both field and container production (*e.g.*, EC-5, 10HS, GS3, 5TE sensors; Decagon Devices, Pullman, WA).

Most soil moisture sensors operate on the principle of electromagnetic technology to approximate substrate moisture content (Dean et al., 1987; Ledieu et al., 1986). However, the sensors come in multiple types, including TDR (Robinson et al., 2003) and capacitance sensors

(Bogena et al., 2007). Time domain reflectometry sensors use an electromagnetic wave propagated through the substrate via a conductor. The velocity of the wave depends on soil's bulk relative permittivity (Topp and Reynolds, 1998). Soil or substrate bulk permittivity is influenced largely by soil moisture content. Capacitance sensors on the other hand measure the combined real dielectric permittivity of various substrate components (air, substrate pore water and substrate particles) (Bogena et al., 2007). The sensor reading is converted into substrate moisture content values through calibration equations stored in software. The substrate-water-air matrix acts as the dielectric of a capacitor and completes an oscillating circuit (Heng et al., 2002) between parallel electrodes whenever the sensors are powered. Air has a dielectric of about 1, soil particles between 3-5, and water about 80 (Hanson and Peters, 2000), and changes in the dielectric permittivity of a soil or substrate are largely due to changes in soil water content. Water has a higher dielectric permittivity because it is a polar molecule. However, despite the availability of soil moisture sensors, their application in irrigation monitoring or control in commercial greenhouse or nursery production systems is still minimal. This may be attributed to a lack of knowledge and awareness among growers and experts to assemble, install and maintain this kind of irrigation system in greenhouses and nurseries.

Irrigation, fertilizer and their interactive effects on container-grown plants

Water and fertilizer are two major production inputs through which growth of plants can be manipulated to achieve desired plant morphology (Groves et al., 1998). Maintaining optimum levels of fertilizer and water in container production is challenging. Container production can inhibit plant growth due to the small substrate volume which holds small amounts of water and fertilizer at a given time (Rouphael et al., 2008). Plants rapidly deplete the water and nutrients in the substrate, creating a need for frequent irrigation. Root growth is also restricted in container grown plants and roots may become deformed (Mathers et al., 2007). To sustain and improve growth and development, irrigation and fertilization are often carried out frequently in the greenhouse (Morvat et al., 1998). While commercial greenhouse growers rely heavily on fertilization and irrigation, plant growth does not always improve with addition of more fertilizer or water (Conover and Poole, 1992; Zheng et al., 2004). Conover and Poole (1992) found that frequent irrigation increased N and P leachate without significant difference in plant quality. In some cases less frequent irrigation has been shown to improve plant growth as well as reduce leaching (Fare et al., 1994). High levels of fertilizer can actually cause a decline in growth (James and Van Iersel, 2001; Dole et al., 1994). The decline in growth at higher fertilizer levels may be due to osmotic stress caused by salts accumulation in the substrate (Yokoi et al., 2002; Rouphael el al., 2008). Inhibition of growth due osmotic stress due to high fertilizer rates is more likely to occur if crops are grown at relatively low substrate water content; this has been reported in New Guinea impatiens (*Impatiens hawkeri*) (Haver and Schuch, 1996). High levels of fertilizer (N) have also been reported to increase plants susceptibility to water stress (Cabrera, 2004). High N levels have been theorized to alter how quickly plants can respond to water stress by regulating their stomatal conductance to control water loss (Marschner, 1995). High levels of N also result in large plants that require more water than smaller plants (Augé and Moore).

Substrate nutrient availability involves intricate interactions with substrate water content. The availability, movement and uptake of nutrients in a substrate largely depend on substrate water content (Nye and Tinker, 1977; De Willigen and van Noordwijk, 1994; Oliet et al., 2004). A small change in substrate water content can result in large alteration in nutrient movement and uptake (Raviv et al., 1999). Nutrient availability also may be affected by substrate water content because more leaching occurs as irrigation volume increases (Lea-Cox et al., 2001). Apart from nutrients, leachate from greenhouse productions systems also contains other agrochemicals, such as pesticides and plant growth regulators (PGR). Plant growth regulators are widely used in ornamental plants production.

Controlled deficit irrigation as an alternative to chemical plant growth regulation

Plant height is an important quality characteristic of ornamental plants and critical for consumer preference (Heins et al., 1999). Consumers tend to prefer high intensity colored, shorter, well-branched plants. Plant height is also important in transportation and postharvest handling of plants. Tall plants occupy larger volumes and are more delicate to transport compared to shorter plants (Hayashi et al., 2001). To achieve the preferred plant height, growers usually use synthetic plant growth regulators (PGRs) to control plant growth (Marosz and Matysiak, 2005; Banon et al., 2002). Plant growth regulators have also been reported to influence flowering and lateral branching as well (Hayashi et al., 2001). A variety of PGRs known by different trade names and active ingredients are used in plant growth regulation. The most common PGRs used in ornamental plants growth regulation include ancymidol, (A-Rest), daminozide (B-Nine) paclobutrazol (Bonzi), flurprimidol, Cycocel), and maleic hydrazide (Kessler and Keever, 1997). Plant growth regulators reduce stem elongation by antagonizing or inhibiting biosynthesis of gibberellins (Lodeta et al., 2010; Brown et al., 1997; Rademacher, 1989).

Plant growth regulators expenses add to the cost of production (Mata and Botto, 2009). Growers also face a variety of risks when using PGRs. Application of too much PGR or at the wrong time may lead to irreversible stunting of plants. However, application of too little may have no effect on stem elongation regulation (Latimer et al., 2001; Al-Khassawneh et al., 2006; Pritchard et al., 1996). If not used properly, PGRs can also cause phytotoxicity (Hamid and Williams, 1997; Gibson et al., 2003). Environmentally, PGRs are also among the agro-chemicals that contribute to agricultural related non-point environmental pollution (Berghage and Heins, 1991). Due to their pollution potential, the use of PGRs has restrictions in some countries (Moe et al., 1992). Regulations limiting PGRs use are likely to increase in the future (Clifford et al., 2004). There is a need for a safer, more reliable and sustainable means of controlling plant growth. Previous work has shown the possibility of regulating stem elongation by reducing temperature (Berghage, 1989; Moe et al., 1992; Bakken and Moe, 1995). However, lowering temperature may also reduce photosynthesis and metabolic processes, including growth rate that can delay crop maturity. Some studies have also shown the possibility of regulating stem elongation in poinsettia through manipulation of light quality (Mata and Botto, 2009; Cockshull et al., 1994). However, manipulating light in greenhouses is difficult and expensive.

Controlled water deficit is a potential viable alternative to PGRs as means of plant growth regulation. Cell expansion declines under water stress and consequently leaf, stem expansion and elongation reduce as the substrate moisture content continues to decline (Sharp, 2002). Water stress results in cell turgor pressure reduction and changes in cell wall properties that control leaf expansion and stem elongation (Singh et al., 2000; Neumann, 1995; Cramer and Bowman, 1991). Thus, regulated water stress can be used to control plant growth (Hendriks and Ueber, 1995; Cameron et al., 2006). Drought severity and frequency are known to result in different levels of growth suppression in many species, such as salvia (*Salvia splendens*), Big Bend bluebonnet (*Lupinus havardii*) and petunia (*Petunia* ×*hybrida*), (Burnett et al., 2005; Niu et al., 2007; van Iersel et al., 2010). Barrett and Nell (1982) also showed a reduction in poinsettia height with an increase in water stress. This technique would be inexpensive and less likely to cause plant damage if monitored carefully. In addition, controlled water deficit is environmentally friendly and may also save water. However, application of controlled water deficit (WD) as a means of plant height regulation has not been popular in the past due to the risk of excessive stress and plant loss. In our previous and current studies, we have employed precision irrigation techniques to control and apply WD. This automated irrigation system uses soil moisture sensors to monitor and maintain desired θ levels (Nemali and van Iersel, 2006), eliminating risk of excessive drought stress and providing precise control over the severity of the drought. Integration of sensor controlled irrigation systems into greenhouse production can thus make WD a viable technique of regulating plant height.

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CHAPTER 3

GROWTH OF PETUNIA AS AFFECTED BY SUBSTRATE WATER CONTENT AND FERTILIZER RATE

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Abstract

Rising concerns over environmental impacts of excessive water and fertilizer use in the horticultural industry necessitate more efficient use of water and nutrients. Both substrate volumetric water content (θ) and fertilizer affect plant growth, but their interactive effect is poorly understood. The objective of this study was to determine the optimal fertilizer rates for petunia (*Petunia ×hybrida*) 'Dreams White' grown at different θ levels. Petunias seedlings were grown at four levels of θ (0.10, 0.20, 0.30, and 0.40 $m^3 \cdot m^{-3}$) with eight different rates of controlled release fertilizer (Osmocote 14-14-14; 14N-6.1P-11.6K; rates of 0 to 2.5 g/plant, equivalent to 0 to 6.25 $kg \cdot m^{-3}$ substrate). Shoot dry weight increased as the fertilizer rate increased from 0 to 1.67 g/plant but decreased at even higher fertilizer rates. The effect of fertilizer rate on growth was more pronounced at higher θ. Leaf size doubled as the θ thresholds increased from 0.10 to 0.40 $m^3 \cdot m^{-3}$. Flowering was reduced by a combination of high fertilizer rates (> 0.63 g/plant) and high θ (0.30 and 0.40 $m^3 \cdot m^{-3}$), indicating that optimal conditions for vegetative growth are different from those for maximal flowering. These results suggest that without leaching, high quality petunias (sufficient biomass and flowers) can be grown with lower fertilizer rates than commercially recommended rates.

Additional index words. Controlled release fertilizer, greenhouse irrigation, *Petunia* × *hybrida,* leaching, soil moisture sensors, volumetric water content, water use, capacitance sensors

Introduction

Fertilizer and irrigation are inseparable components of ornamental plant production. Nutrient availability to the roots is dependent on θ, since nutrient movement is driven by mass flow and diffusion (Nye and Tinker, 1977; De Willigen and van Noordwijk, 1994; Brown and van den Driessche, 2002). Greenhouse crops typically grow in containers with a limited amount of substrate from which water and nutrients are rapidly depleted (Rouphael et al., 2008). Thus, frequent irrigation and fertilization may be required to sustain high growth rates (Cabrera, 2005). However, this does not always improve crop quality (Zheng et al., 2004), because plant growth is not enhanced by fertilizer application above an optimum rate (van Iersel et al., 1998). Growth rates may actually decline at super-optimal fertilizer rates (James and van Iersel, 2001; Dole et al., 1994) due to increased salinity (Rouphael el al., 2008; Kang and van Iersel, 2009), and nutrient toxicity (Chen et al., 2001). Excessive fertilization also inhibits flowering in ornamentals, such as *Rosa × hybrida* 'Baccara' (Plaut et al., 1973) and *Dianthus caryophyllus* 'Santorini' (Taylor et al., 2004).

Commercial greenhouse growers rely heavily on application of water and fertilizer to maximize production, but often pay less attention to their use efficiency and environmental sustainability (Pinto et al., 2008). Efficient water and nutrient management is an increasingly important aspect of greenhouse production, because excessive irrigation leads to nutrient leaching and runoff, which has serious environmental consequences. Government regulations increasingly require growers to minimize their environmental impact (Lea-Cox and Ross, 2001; Majsztrik et al., 2011). Efficient fertilizer management is also economical, because of the increasing price of fertilizer (Majsztrik et al., 2011). Furthermore, leaching compromises production efficiency by removing fertilizer from the root zone (Ristvey et al., 2001; Mikkelsen et al., 1994) and lowering nutrient use efficiency (Bilderback, 2002; Shaviv and Mikkelsen, 1993). Nutrient removal from the root zone is influenced by irrigation method, substrate porosity and fertilizer regime (James and van Iersel, 2001). Less precise irrigation methods, such as overhead sprinklers, result in more leaching than drip irrigation (Majsztrik et al., 2011) Application of water-soluble fertilizers is also likely to result in more leaching than controlled-release fertilizer (CRF). Controlled-release fertilizer (CRF) can be used to provide plants with adequate nutrition and minimize runoff because CRFs release nutrients gradually (Cox, 1993; Broschat and Moore, 2007), and are less prone to leaching than water-soluble fertilizers (Hershey and Paul, 1982; Chen et al., 2001). However, leaching can still occur with CRFs (Broschat, 1995), because initial nutrient release rates are often high and increase as substrate temperature rises (Adams et al., 2003; Birrenkott et al., 2005; Broschat, 1996; Merhaut, et al., 2006). And over-irrigation can leach out nutrients that have accumulated in the root zone.

Timers are commonly used to control greenhouse irrigation and provide water according to a predetermined schedule. This may result in unnecessary water applications and leaching since a set irrigation volume is provided regardless of θ or plant water status. Precision irrigation systems, based on sensor measurements of θ, can be used instead of timer-controlled systems to maintain a consistent θ with little or no leaching (Nemali and van Iersel, 2006). Sensor-controlled irrigation, combined with CRF, allows for precise control of plant water and nutrient availability. These systems can reduce water (Chappell et al., 2013) and CRF use (Bayer et al., 2014) in ornamental production, and could be utilized to control plant morphology by altering θ and fertilization rates (Groves et al., 1998). Little is known about the interactive effects of θ and fertilization in container-grown plants. Relatively low θ and high fertilization rates increase substrate EC and inhibit growth by imposing osmotic stress in New Guinea impatiens (*Impatiens hawkeri*) (Haver and Schuch, 1996). Nutrient availability may also be affected by θ because more leaching occurs as irrigation volume increases (Lea-Cox et al., 2001). Drawing on our preliminary data and previous studies (Bayer et al., 2014; Chappell et al., 2013; Nemali and van Iersel, 2006), we hypothesize that by minimizing or eliminating leaching through precision irrigation control, growers can reduce fertilizer application rates. The objectives of this experiment were to: 1) quantify the interactive effects of fertilizer rate and substrate water content on the growth of petunia; 2) determine the optimum substrate water content and fertilizer rate for the production of high quality plants without leaching, and 3) to quantify the effect of environmental conditions on plant water use.

Materials and Methods

Plant material and treatments. Petunia 'Dreams White' seedlings were obtained from a commercial greenhouse (Tagawa Greenhouses, Brighton, CO). Controlled-release fertilizer (Osmocote 14-14-14; 14N-6.1P-11.6K; The Scotts Co., Marysville, Ohio) was incorporated at eight different rates (0, 0.21, 0.42, 0.63, 0.83, 1.25, 1.67 or 2.50 g/plant; 1 g/plant is equivalent to approximately 2.5 $kg \cdot m^{-3}$) into a peat: perlite (80:20) substrate (Fafard 1P; Fafard, Agawam, MA; pH range: 5.5 to 6.5 after wetting). The substrate also contained starter nutrients, a wetting agent, and dolomitic limestone, which was the main source of Mg and Ca for the plants. Thirty two rectangular trays (36 × 24.4 × 10 cm) were filled with substrate after which fertilizer was incorporated at the eight different rates. Twenty-four uniform seedlings (approximately 5 cm tall) were transplanted into each of the 32 trays and hand-watered for one week to allow for root establishment.

Subsequent irrigation was controlled using an automated soil moisture sensor-controlled system based on the design by Nemali and van Iersel (2006). Threshold θ levels of 0.10, 0.20, 0.30, or 0.40 $m^3 \cdot m^{-3}$ and the eight fertilizer treatments were assigned to the 32 trays in a factorial design. Two capacitance soil moisture sensors (EC-5; Decagon, Pullman, WA) were inserted diagonally into the substrate of each tray, and connected to a data logger (CR10; Campbell Scientific, Logan, UT) through two multiplexers (AM16/32; Campbell Scientific). Measurements were taken every 10 min using a 2.5 V excitation voltage supplied by the data logger. The sensors' raw voltage output was converted to θ using a substrate-specific calibration (θ = voltage × 1.8862 - 0.5624, $r^2 = 0.95$). Whenever the average θ for an individual tray fell below the threshold θ, the data logger sent a signal to a relay driver (SDM-CD16AC/DC controller; Campbell Scientific), which opened a solenoid valve (X-13551-72; Dayton Electric Co., Niles, IL) for 20 s to irrigate the tray through two pressure-compensated emitters and a custom-made irrigation grid, supplying 3.7 mL/plant during each irrigation event.

Data collection. The data logger recorded the number of irrigation events daily, and the average θ for each tray every 2h throughout the study. Daily and total irrigation volumes were calculated using the known volume per irrigation event. Total evapotranspiration (ET) from each tray was calculated as the sum of the total amount of irrigation water applied and the change in the amount of water in the substrate over the course of the study (Total ET = total irrigation + (initial θ – final θ) × substrate volume). Pore water electrical conductivity (EC) was measured on days 5, 6, 7, 8, 12, 13, 14, 20 and 23 after transplanting using a handheld probe (SigmaProbe, Delta T Devices, Cambridge, UK). Leaf chlorophyll content was measured twice on four recently matured, fully-expanded leaves from two plants per treatment using a chlorophyll meter (SPAD 502, Konica Minolta Sensing Americas, Ramsey, NJ). At the end of the experiment (day 23), plants were visually evaluated for flower quality, and ten fully expanded leaves were randomly sampled from the plants in each container and measured using a leaf area meter (LI-3100, Li-Cor, Lincoln, NE). The shoots were then cut off at the substrate surface and dried in an oven for one week at 80 °C, and dry weight was determined. Shoot nutrient concentrations were subsequently analyzed at the USDA-ARS Application Technology Research Unit (Toledo, OH). The trays with substrate were weighed after harvesting the shoots, dried, and reweighed to gravimetrically quantify their water content.

Environmental conditions. Plants were grown on a bench in a glass-covered greenhouse at the University of Georgia, Athens, GA. Temperature and relative humidity (RH) in the greenhouse were measured every 20 seconds using a temperature and humidity probe (HMP60, Vaisala Inc., Woburn, MA). Light (photosynthetic photon flux, *PPF*) was measured using a quantum sensor (QSO-sun; Apogee Instruments, Logan, UT). All sensors were connected to the data logger, which stored daily temperature extremes and average *PPF* and RH values, and calculated saturation vapor pressure (VP) and vapor pressure deficit (VPD) using the temperature and RH data, and daily light integral (DLI) from the *PPF* data. Daily maximum and minimum temperature averaged 28.4 ± 2.6 and 19.0 ± 2.1 °C respectively, while the DLI averaged 15.9 ± 2.5 $mol \cdot m^{-2} \cdot d^{-1}$ (means ± SD).

Experimental design and data analysis. The study consisted of a completely randomized factorial design (four θ treatments × eight fertilizer rates). The experimental unit was a container with 24 plants. The data were subjected to multiple regression analysis using SAS (SAS Institute, Cary, NC). To quantify the effects of θ and fertilizer rate on the measured parameters, linear and quadratic effects of θ and fertilizer rate as well as the interactive effect were included in the model. Significant effects were then determined using stepwise forward selection at $P < 0.05$ (proc REG; SAS).

The effects of environmental conditions on plant water use were determined using the data from plants grown with a θ threshold of 0.40 $m^3 \cdot m^{-3}$ and a fertilizer rate of 1.67 g/plant. This treatment was chosen because it produced the largest plants with the highest total irrigation volume. Stepwise forward selection regression analysis ($P < 0.05$, proc REG; SAS) was used to evaluate the effects of DLI, days after transplanting, average daily VPD, temperature and their two way interactions on daily water use.

Results and Discussion

Substrate volumetric water content. Automatic irrigation commenced once the substrate dried out to below the threshold θ, which took one (0.40 $m^3 \cdot m^{-3}$ θ threshold) to two weeks (0.10 $m^3 \cdot m^{-3}$ θ threshold). Thereafter, θ was consistently maintained close to threshold levels (Fig. 1), despite changes in environmental conditions or increased transpiration rates due to plant growth over time, similar to previous findings (Nemali and van Iersel, 2006). Moisture sensor readings were strongly correlated to gravimetrically-determined θ at the end of the study (*r* = 0.94, results not shown).

Pore water electrical conductivity (EC). Stepwise regression analysis indicated that pore water EC was not affected by the θ threshold, while there was a quadratic effect of both fertilizer rate and time (days after transplanting). There were no significant interactions between time, fertilizer rate, and θ threshold. Averaged over the course of the study, pore water EC increased from 1.2 to 3.6 $dS{\cdot}m^{-1}$ as fertilizer rate increased from 0 to 2.5 g/plant (Fig. 2). Approximately 63% of the variation in pore water EC could be explained based on the effects of fertilizer rate, while the decrease over time accounted for an additional 13% of the variation. Regardless of θ and fertilizer rate, pore water EC decreased by approximately 1.17 $dS{\cdot}m^{-1}$ from transplanting to the end of the experiment (23 d). Since there was no leaching, this decrease was due to plant nutrient uptake.

Pore water EC may decline with increasing θ because of dilution (Scoggins and van Iersel, 2006) or as the result of increased plant nutrient uptake due to faster growth. Bulk EC determined from saturated substrate paste (Hershey, 1989) has been found to increase under low θ conditions when high rates of CRF are applied (Haver and Schuch, 1996). We observed no effect of θ on pore water EC, possibly due to enhanced nutrient release from the CRF at higher θ thresholds (Du et al., 2006), although Adams et al. (2013) concluded that this effect was minimal at best.

Shoot dry weight. There was a quadratic effect of fertilizer rate, a positive, linear effect of θ, and an interactive effect of θ and fertilizer rate on shoot dry weight (Fig. 3; Table 2). Shoot dry weight increased as fertilizer rates increased from 0 to approximately 1.67 g/plant at all θ thresholds and decreased again as the fertilizer rate increased further to 2.5 g/plant. Maximum shoot dry weights were achieved with fertilizer rates of 1.3 to 1.67 g/plant, corresponding to an average pore water EC of 3.1 to 3.4 $dS{\cdot}m^{-1}$ (Fig. 2). The decrease in shoot dry weight at high fertilizer concentration was possibly caused by an increase in salt concentration in the substrate pore water (average pore water EC of 3.6 $dS{\cdot}m^{-1}$ at the 2.5 g/plant fertilizer rate, Fig. 2), causing osmotic stress (Morgan and Reed, 1998). The interactive effect of θ and fertilizer rate on shoot dry weight indicates that increasing fertilizer rates stimulated plant growth more as the θ threshold increased. Fertilizer concentration (Frett et al., 1985; James and van Iersel, 2001) and θ threshold (van Iersel at al., 2010; Kim et al., 2011) are known to affect petunia shoot dry weight, but interactive effects have not been previously reported.

Shoot nutrient concentrations. There was no significant main effect of θ on shoot concentrations of any nutrient. Shoot N concentrations increased with fertilizer rate up to approximately 1.25 g/plant, with little response to further increases in fertilizer rate (Fig. 4). More than 91% of the variation in shoot N concentration was explained by fertilizer effects (Table 1). There was also an interactive effect of fertilizer rate and θ on shoot N concentration (Fig.4; Table 1). Decreases in shoot N concentration in response to increasing θ were larger at higher fertilizer rates (Fig.4). This effect was highly significant but explained only 3% of the variation in shoot N (Table 1) and may be due to N dilution resulting from the positive effect of θ on shoot dry weight (Fig. 3).

Fertilizer rate had a quadratic effect on shoot P, K, and Mg concentrations (Fig. 4; Table 1), which increased with increasing fertilization rates in the 0 - 1.25 g/plant treatments. Higher fertilizer rates had little additional effect on shoot P and K concentrations. Shoot Mg concentrations decreased as fertilizer rates increased to 1.67 and 2.5 g/plant. The fertilizer did not contain Mg and increasing the fertilizer rate therefore did not increase the Mg supply to the plant. There was no effect of θ, fertilizer rate, or their interaction on Ca and S concentrations (results not shown). Shoot Ca and S concentrations averaged 1.35 and 0.41 $mg \cdot g^{-1}$, respectively.

Micronutrient shoot concentrations had no (Fe and Mo) or a weak (Zn, B, Mn and Cu) relationship (total r^2 < 0.50, Table 1) with fertilizer rate. There was a weak interaction of fertilizer rate and θ on the concentration of Cu and B in the shoot (partial R^2 = 0.13 for both). Zinc, B, Mn and Cu concentrations ranged from 61.7 to 90.1, 18.0 to 18.7, 99 to 147 and 4.1 to 3.4 $\mu g \cdot g^{-1}$, respectively at fertilizer rates of 0 to 2.5 g/plant. The lack of strong relationships between micronutrients and fertilizer rate may be because the fertilizer contained no micronutrients. Most of the micronutrients in the plant tissue likely came from the starter fertilizer incorporated into the substrate during manufacturing. Tissue nutrient concentrations for most of the macro- and micronutrients were above the minimum of the range reported for petunia (Mills and Jones, 1996), except for the plants that were not fertilized.

Water Use. Total irrigation volume was affected by θ (partial R^2 = 0.60) and fertilizer rate (partial R^2 = 0.17, Table 2). Total irrigation volume increased by 215 mL/plant as the irrigation θ threshold increased from 0.10 to 0.40 $m^3 \cdot m^{-3}$ (Table 2, Fig. 5). Previous work with similar irrigation systems also showed an increase in total irrigation volume with an increase in θ threshold (van Iersel et al., 2010; Burnett and van Iersel, 2008). Increasing the fertilizer rate from 0 to 1.67 g/plant increased the total irrigation volume by 91 mL/plant, regardless of the θ threshold. Total irrigation volume decreased slightly as the fertilizer rate increased from 1.67 to 2.5 g/plant (Table 2, Fig. 5).

Consistent with previous findings (van Iersel et al., 2010; Kim et al., 2011), shoot dry weight was strongly correlated with both total irrigation volume and ET with slopes of 2.51 and 3.51 $g \cdot L^{-1}$, respectively (Fig. 7). The slope of the dry weight vs. irrigation volume was similar to previous findings (2.54 and 2.45 $g \cdot L^{-1}$; van Iersel et al., 2010; Kim et al., 2011). Although we have previously referred to the slope of shoot dry weight vs. irrigation volume as water use efficiency (van Iersel et al., 2010; Kim et al., 2011), this slope does not reflect water use efficiency in the traditional sense (dry weight produced per unit water applied). It does, for example, not take into account possible differences in water use efficiency among the treatments.

For the plants grown with a 0.40 $m^3 \cdot m^{-3}$ θ threshold and 1.67g/plant fertilizer rate, most of the day-to-day variation in irrigation volume was explained by the interaction between days after transplanting (a proxy for plant age or size) and DLI (r^2 = 0.96). Daily irrigation volume generally increased over time because plant size increased (Fig. 6). The effect of DLI on daily irrigation volume increased as the plants got larger, because canopy light interception, which depends on DLI and canopy size, has a strong impact on plant water use (Kim et al., 2011). van Iersel et al. (2010) also reported an interactive effect of DLI and plant age on the water use of petunia.

Other environmental variables, such as temperature and VPD, also can affect water use of ornamental greenhouse crops (Baille et al., 1994; Kim and van Iersel, 2009), but were not statistically significant in this study. However, we cannot rule out the possibility that these variables affected daily irrigation volume, because there were strong correlations between VPD and DLI (r = 0.92) and temperature and day (r = -0.90). Thus, it was difficult to distinguish between the effects of temperature and day, or of VPD and DLI.

Leaf size. The area of the uppermost fully expanded leaves increased with increasing θ threshold and this effect was more pronounced at higher fertilizer rates (Fig. 3). Most of the variation in leaf size was explained by θ threshold (partial R^2 = 0.71; Table 2). There was a weak interactive effect of fertilizer rate and θ (partial R^2 = 0.092; Table 2). Leaf size approximately doubled as the θ threshold increased from 0.10 to 0.40 $m^3 \cdot m^{-3}$ (Fig. 6). A decrease in leaf expansion is among the first indicators of drought stress and is very sensitive to substrate water availability (Kalapos et al., 1996; Fernandez et al., 2002).

Flowering. Flowering is an important ornamental quality trait of petunia. Plants grown at lower fertilizer rates and θ thresholds had more flowers (Fig. 8) than those with the highest shoot dry weights and leaf areas (Fig. 3). Maximum shoot dry weight was achieved with 1.3 to 1.67 g/plant fertilizer and a θ threshold of 0.40 $m^3 \cdot m^{-3}$ (Fig. 3), but maximum flowering occurred with the 0.21 to 0.63 g/plant fertilizer rates and θ thresholds of 0.20 $m^3 \cdot m^{-3}$. A similar relationship between flowering and fertilizer rate was described by James and van Iersel (2001); flowering of subirrigated petunia and wax begonia (*Begonia* ×*semperflorens*) increased with an increase in fertilizer solution EC from 0.15 to 1.8 dS·m^{-1}), while flower number decreased (begonia) or was similar (petunia) at even higher fertilizer solution EC. The fertilizer rates that produced maximum flowering (0.21 to 0.63 g/plant) were much lower than the commercially recommended rates (1.01 to 3.26 g/plant). The use of precision irrigation prevented nutrient leaching from the substrate, thus reducing the fertilizer requirements of the crop.

Leaf chlorophyll content. The average leaf chlorophyll content increased with an increase fertilizer rate (*partial* r^2 = 0.15). However, leaf chlorophyll content also decreased over time, but the decrease was depended on fertilizer rate and θ thresholds (*partial* r^2 = 0.17). Chlorophyll content increased with increasing fertilizer rate at the 0.10 $m^3 \cdot m^{-3}$ θ threshold, but this response was less pronounced at higher θ thresholds and absent at 0.40 $m^3 \cdot m^{-3}$ (Fig. 9). Leaf chlorophyll content is a known indicator of plant health and leaf nitrogen content (*e.g.*, Yoder and Crosby, 1995). Leaf chlorophyll content was correlated with N (r = 0.54, p = 0.0015), P (r = 0.49, p = 0.0048), K (r = 0.46, p = 0.0086), S (r = 0.53, p = 0.0013), and Zn (r = 0.40, p = 0.023).

Conclusions

The sensor-controlled irrigation system effectively maintained θ close to treatment threshold levels with little or no leaching. High quality petunias (sufficient foliage and flowers) were grown with CRF rates much lower than commercially recommended. Shoot dry weight increased with an increase in fertilizer rate, but the increase depended on θ. Plants grown at higher θ thresholds had larger changes in shoot growth with an increase in fertilizer rate. Leaf size also increased with increasing fertilizer rate and this effect was more pronounced at higher θ thresholds. However, lower fertilizer rates resulted in more flowers. Since vegetative growth responded differently to fertilizer and θ than flowering, growers can adjust fertilizer rates and θ to manipulate growth and development of petunia.

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Table 3.1. Regression coefficients, *P* values, and R^2 values from multiple regression analysis of the effects of substrate volumetric water content (θ), fertilizer rate, and their interaction on shoot nutrient concentrations ($y = x_0 + x_1 \times \theta + x_2 \times \text{Fertilizer} + x_3 \times \theta \times \text{Fertilizer} + x_4 \times \theta^2 + x_5 \times \text{Fertilizer}^2$, where $x_0, \ldots, x_5$ are regression coefficients). There was no significant effect of θ or θ^2 on any of the nutrients, while there were no significant treatment effects at all on Ca, S, Fe, and Mo (*P* > 0.05).

Nutrient		Intercept	Fertilizer	θ*Fertilizer	Fertilizer^2	Total R^2
N	Coefficient	2.214	4.449	-1.843	-0.956	
	P value		<0.0001	0.0005	<0.001	
	Partial R^2		0.766	0.030	0.149	0.945
P	Coefficient	0.5017	0.73392		-0.20477	
	P value		<0.0001		<0.0001	
	Partial R^2		0.530		0.24	0.77
K	Coefficient	4.110	3.23424		-0.64512	
	P value		<0.0001		0.0037	
	Partial R^2		0.747		0.065	0.81
Mg	Coefficient	0.8299	0.35696		-0.16525	
	P value		0.0003		0.0447	
	Partial R^2		0.318		0.128	0.445

Cu	Coefficient	3.406		-0.834		
	P value			0.0421		
	Partial R^2			0.131		0.131
Mn	Coefficient	106.9	20.006			
	P value		0.0009			
	Partial R^2		0.314			0.314
B	Coefficient	14.78			0.599	
	P value				0.0425	
	Partial R^2				0.130	0.130
Zn	Coefficient	67.75	10.008			
	P value		<0.0001			
	Partial R^2		0.457			0.457

Table 3.2. Statistical analysis of the effects of substrate water content (θ) threshold and fertilizer rate on irrigation volume, shoot dry weight (DW), leaf size, and leaf chlorophyll content. There was no quadratic effect of θ on any of the measured variables. Responses were analyzed using $y = x_0 + x_1 \times \theta + x_2 \times \text{Fertilizer} + x_3 \times \theta \times \text{Fertilizer} + x_4 \times \theta^2 + x_5 \times \text{Fertilizer}^2$, where y is the measured variable of interest and $x_0, \ldots, x_5$ are regression coefficients.

Variable		Intercept	θ	Fertilizer	θ*Fertilizer	Fertilizer^2	Total R^2
Total Irrigation volume ($m^3 \cdot m^{-3}$)	Coefficient	-28.0	714.8	207.6	ns [a]	- 71.64	
	P		< 0.0001	0.0003		0.024	
	Partial R^2		0.60	0.11		0.06	0.77
Shoot DW (g/plant)	Coefficient	0.268	0.795	0.700	0.584	-0.278	
	P		0.019	< 0.0001	< 0.0001	0.001	
	Partial R^2		0.04	0.19	0.45	0.18	0.85
Leaf size (cm^2)	Coefficient	8.02	25.46		6.064		
	P		<0.0001		0.0013		0.80
	Partial R^2		0.71	ns [a]	0.09	ns [a]	

[a] non-significant

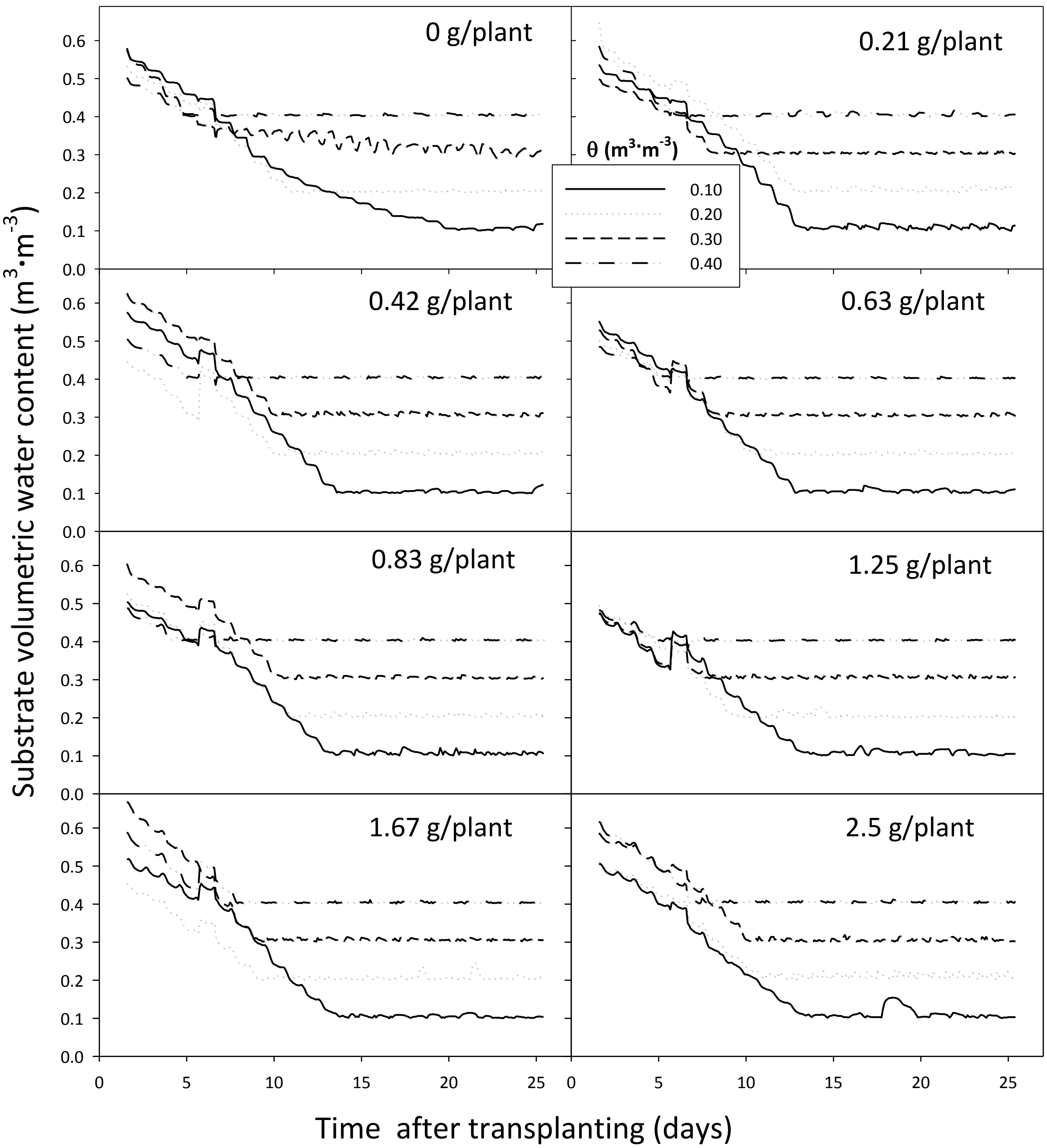

Fig. 3.1. The substrate volumetric water content (θ) in each treatment as maintained by a soil moisture sensor-controlled irrigation system. The values in the top right corner of each graph represent the amount of controlled release fertilizer incorporated into the substrate.

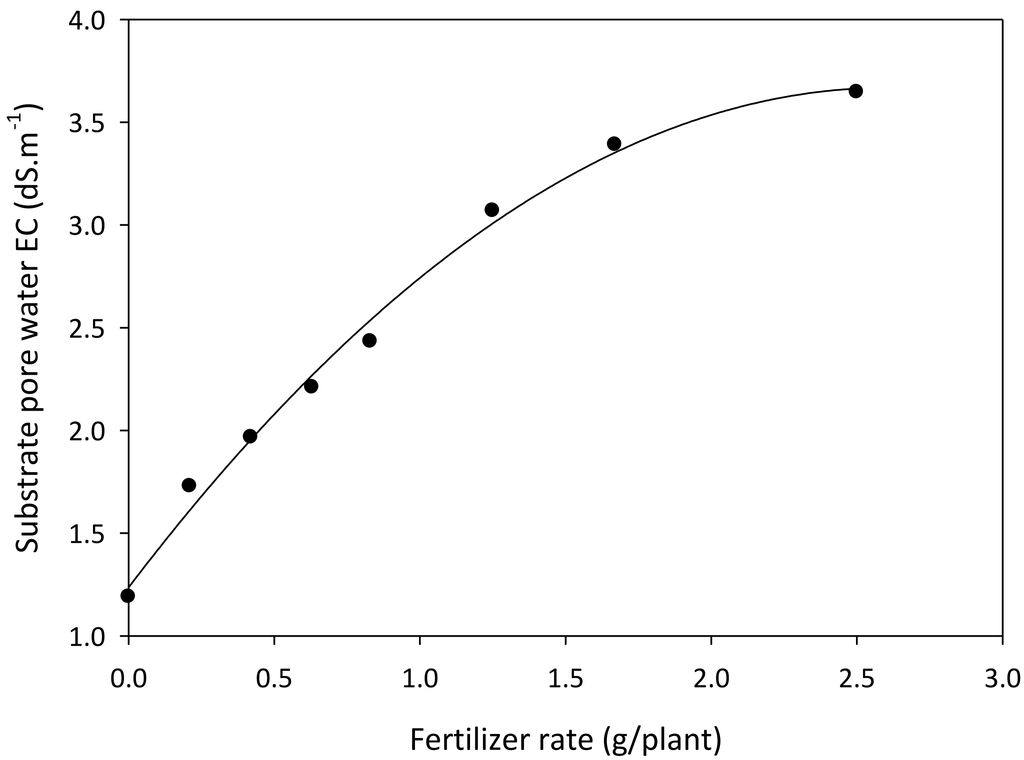

Fig. 3.2. Pore water electrical conductivity (EC) as a function the amount of controlled release fertilizer incorporated into the substrate. Each data point represents the pore water EC averaged over all four substrate water content thresholds and all nine measurement days. Substrate water content did not affect pore water EC, while EC decreased over time (Pore water EC = 1.56 + 0.0776×Fertilizer Rate - 0.00221×Time^2 - 0.000619×Fertilizer Rate^2; r^2 = 0.77).

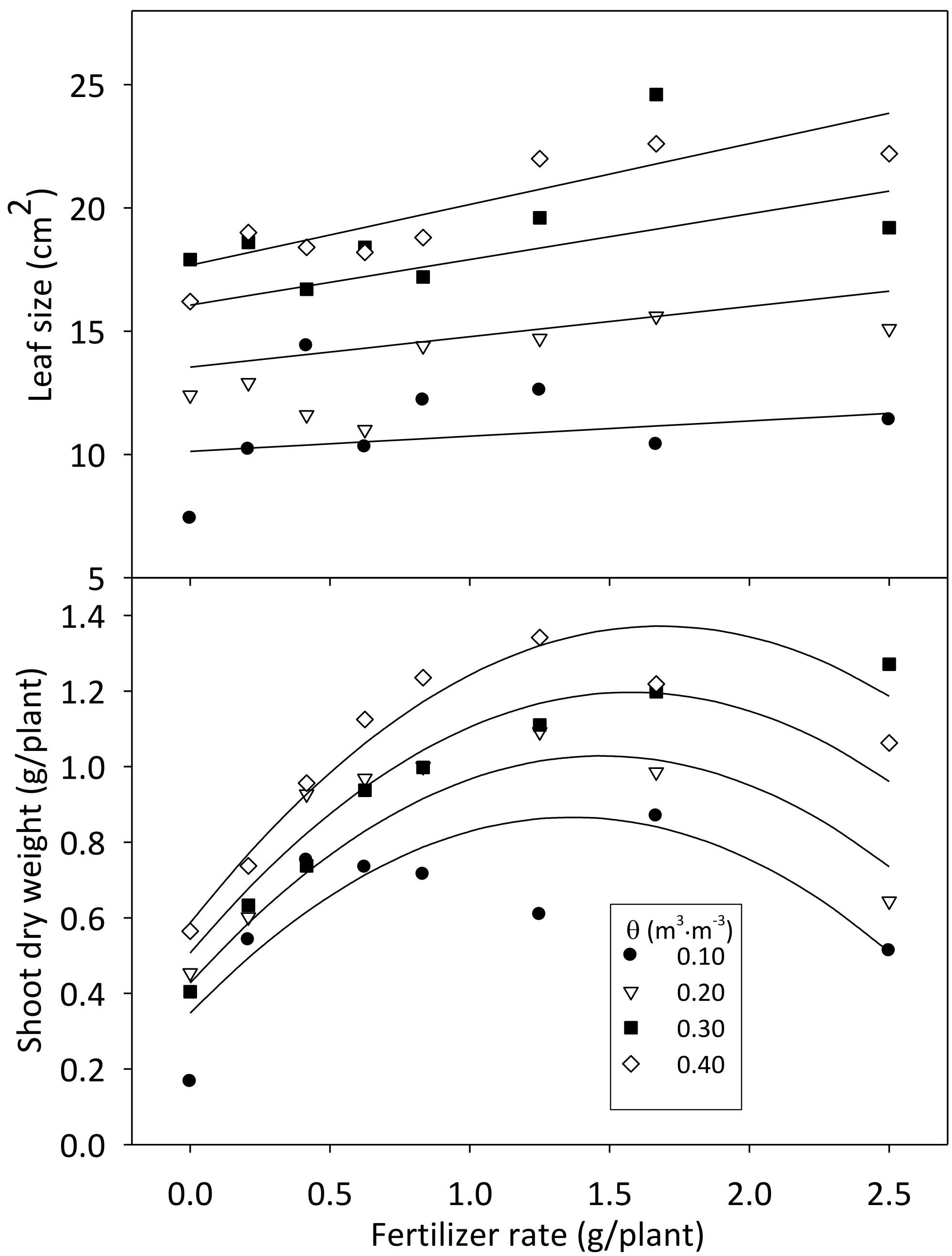

Fig. 3.3. Response of leaf size (area of the upper-most, fully expanded leaf) and shoot dry weight of petunias to different rates of controlled release fertilizer at four different substrate water contents (θ). Curves indicate multiple regression results (Table2).

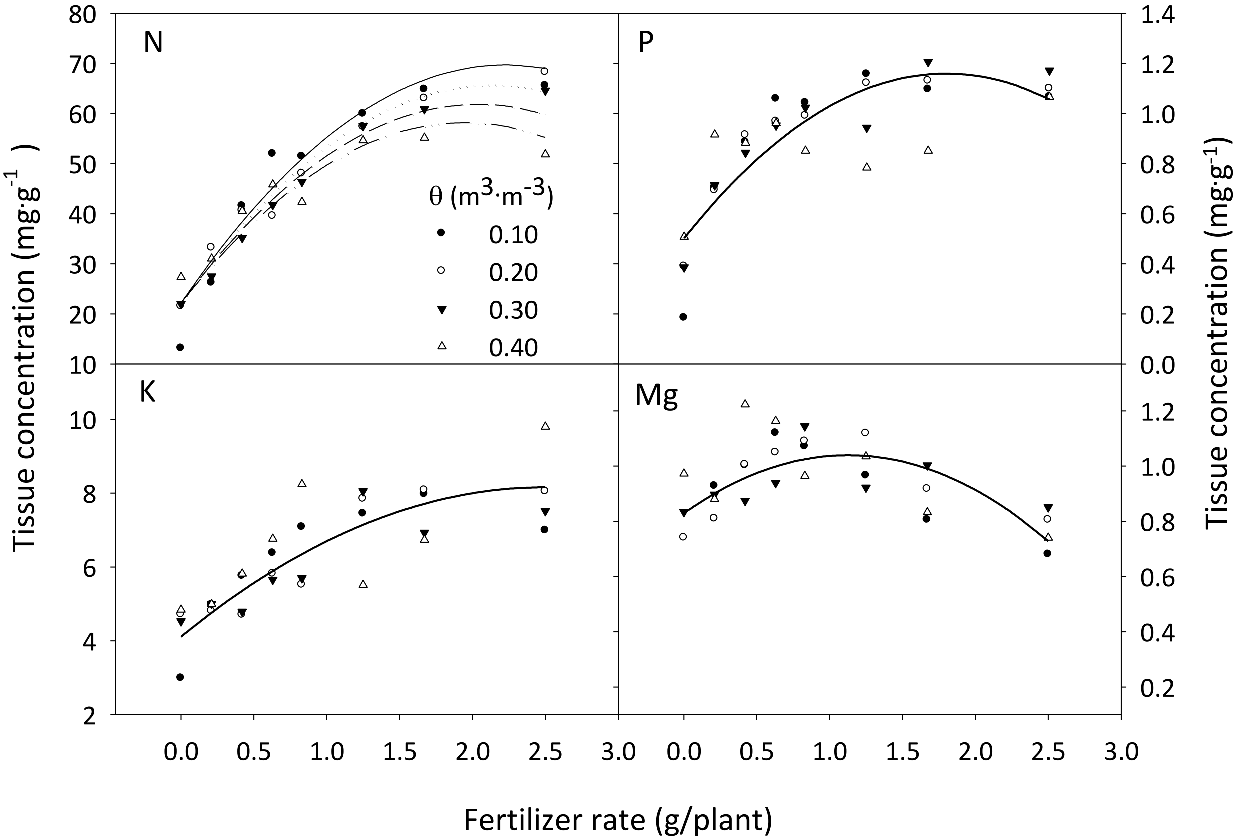

Fig. 3.4. Shoot nutrient concentrations of N, P, K, and Mg as affected by substrate volumetric water content (θ) and fertilizer rate. Symbols indicate measured tissue nutrient concentrations, while the curves show regression results (see Table 1 for regression equations). There was no effect of θ or interactive effect of θ and fertilizer rate on tissue P, K, and Mg and the regression curves for those nutrients show the quadratic effect of fertilizer rate.

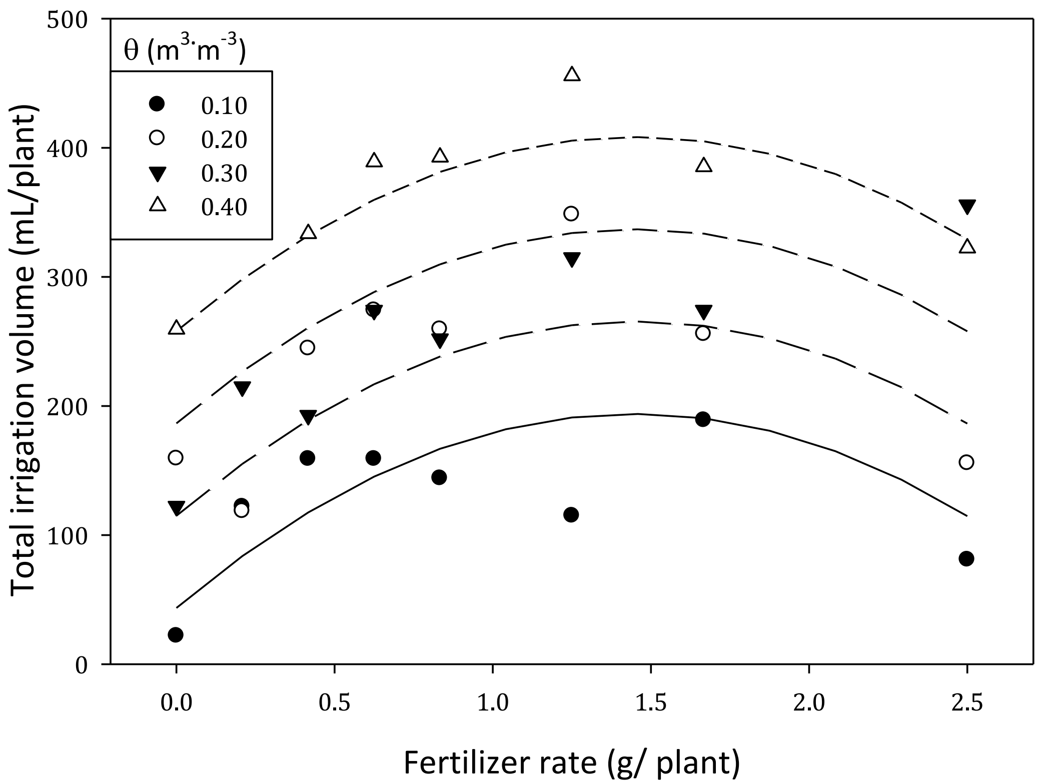

Fig. 3.5. The effect of fertilizer rate and substrate water content (θ) on the total irrigation volume of petunias over a 23-d growing period. There was a quadratic effect of fertilizer rate and a linear effect of θ on irrigation volume, but no interactive effect (see Table 2).

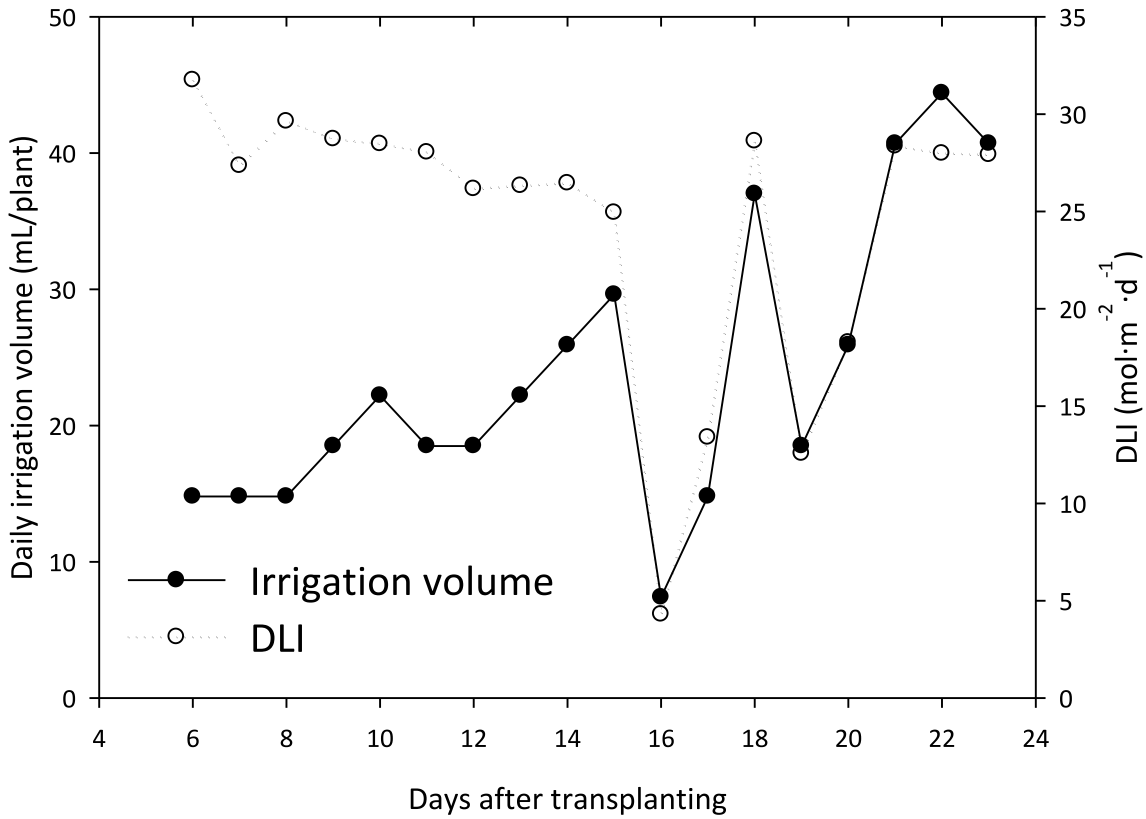

Fig. 3.6. The daily light integral (DLI) and daily irrigation volume of petunia over a 23-d growing period. The plants were grown with a θ threshold of 0.40 $m^3 \cdot m^{-3}$ and a fertilizer rate of 1.25 g/plant. Daily irrigation volume = 1.44 + 0.06569×Day×DLI (r^2 = 0.96, P = <0.0001).

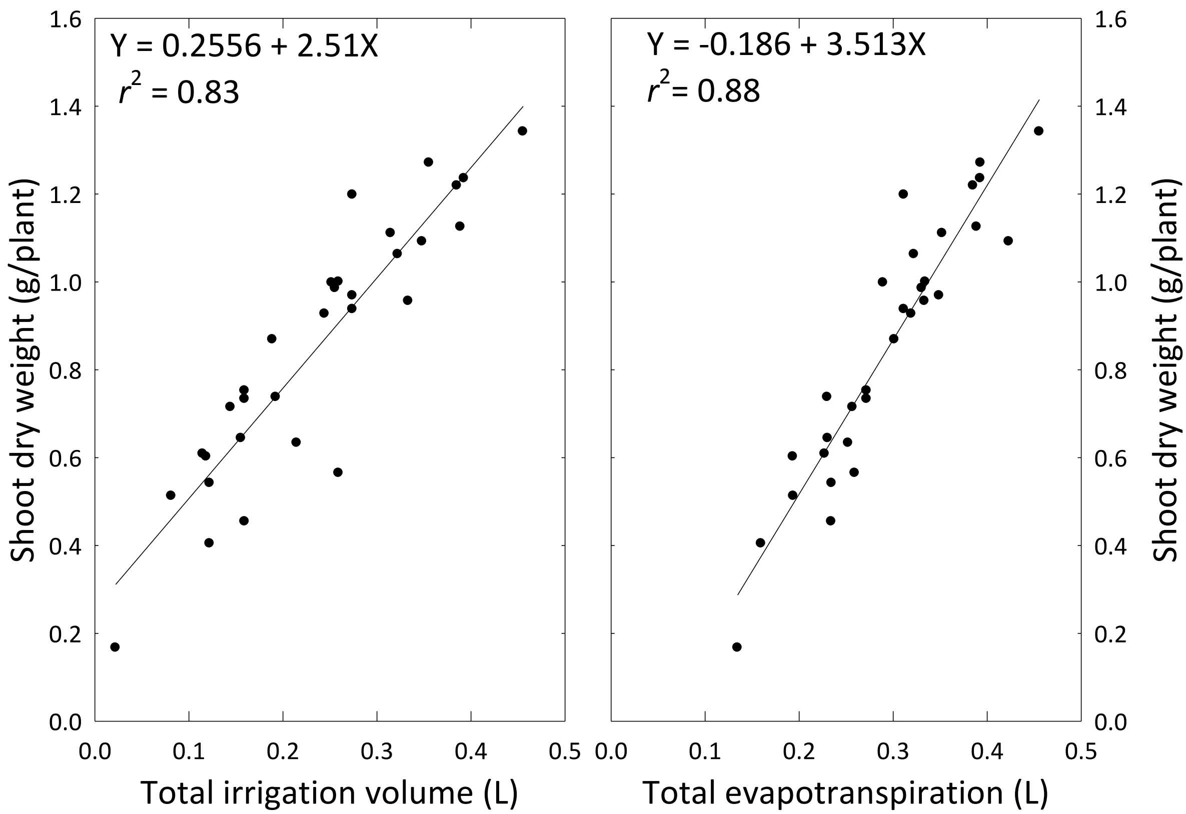

Fig. 3.7. The shoot dry weight as a function of total irrigation volume (left) and total evapotranspiration (right) from the start of the irrigation treatments to the end of the experiment (after 23 d).

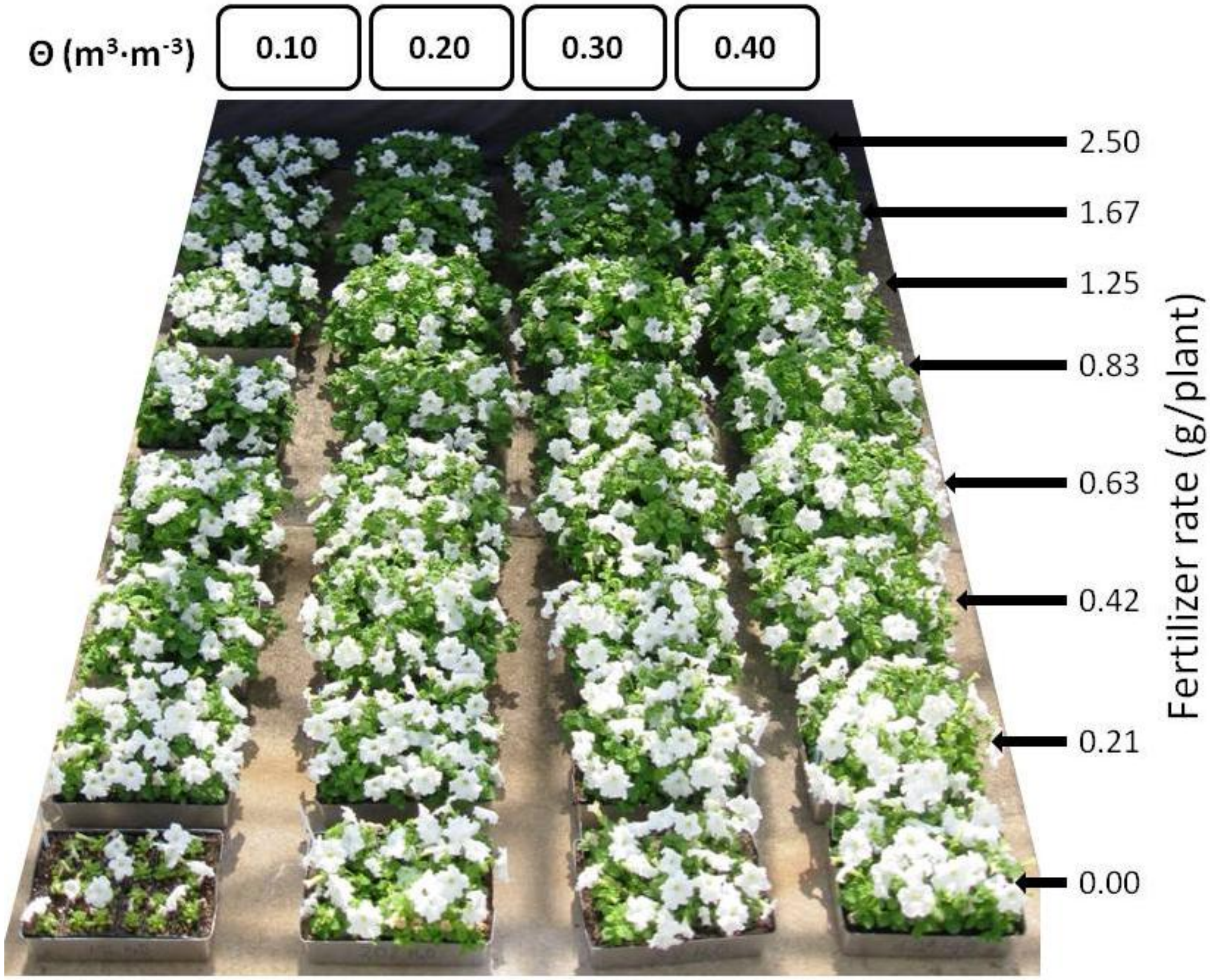

Fig. 3.8. Appearance of petunias at harvest (23 d after transplanting) as affected by the rate of controlled release fertilizer and substrate water content (θ). Flowering was reduced by the combination of high fertilizer rates (> 0.63 g/plant) and high θ (0.20 to 0.40 $m^3 \cdot m^{-3}$).

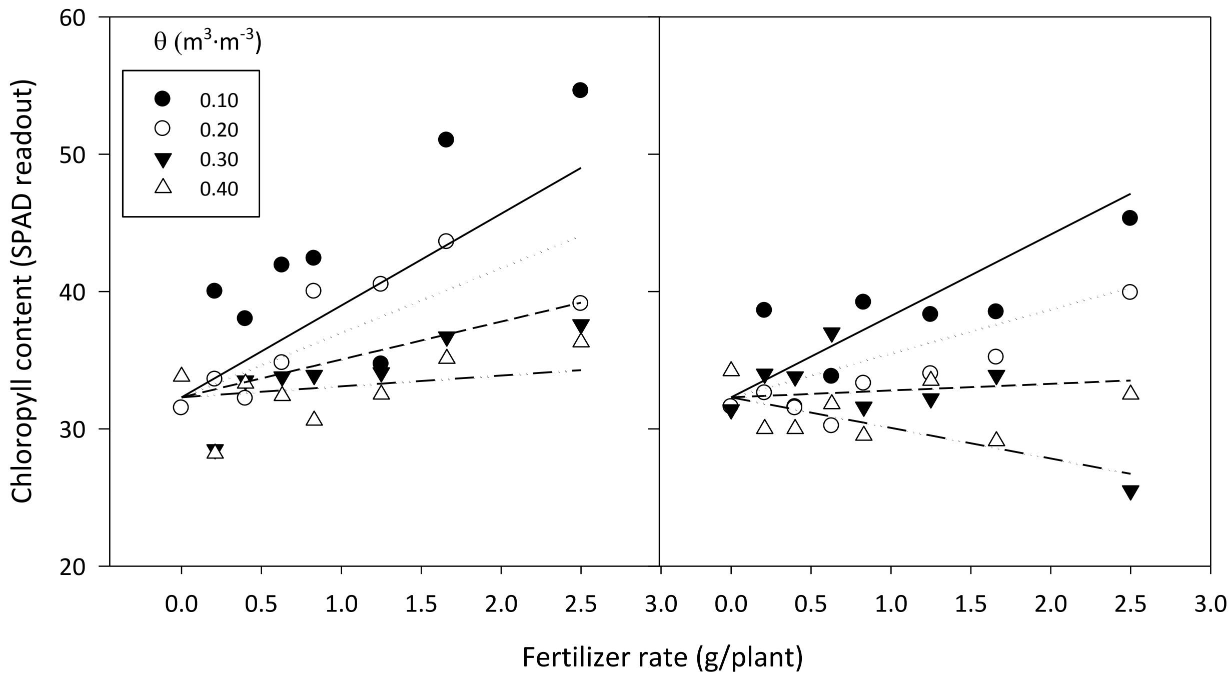

Fig. 3.9. The leaf chlorophyll content of petunia measured on 13th (left) and 18th (right) day after transplanting as affected by fertilizer rate, time (days after transplanting) and substrate water content (θ). The lines indicate the results from the regression analysis (Chl content = 32.29 + 8.65×Fertilizer rate – 1.511×Day×θ×Fertilizer rate, r^2 = 0.32.

CHAPTER 4

IRRIGATION VOLUME AND FERTILIZER CONCENTRATION EFFECTS ON LEACHING AND GROWTH OF PETUNIA

Alem, P.O., Thomas, P.A. and van Iersel, M.W. 2014. Published in *Acta Hort.* 1034:143-148.

Abstract

Excessive irrigation in greenhouse production causes leaching of water with dissolved nutrients. This leaching causes a direct economic loss to growers by removing fertilizer from the pots and potentially causes environmental pollution. Improving irrigation efficiency can reduce leaching, decrease the amount of fertilizer needed and improve both economic and environmental sustainability. Our objective was to quantify the interactive effect of fertilizer concentration and irrigation volume on leaching and growth of petunia (*Petunia × hybrida*) and determine whether growers can use less fertilizer if they irrigate more efficiently (with little or no leaching). Petunia seedlings were grown to a salable size in 15-cm pots filled with peat:perlite (80:20) substrate using two concentrations of N (at 100 and 200 $mg·L^{-1}$) of water soluble fertilizer (15N–2.2P–12.5K) injected into a drip irrigation system resulting in an EC of 1.12 and 2.45 $dS·m^{-1}$ respectively. An automated irrigation system opened a solenoid valve to drip irrigate the plants when substrate moisture content (θ) dropped below 0.45 $m^3·m^{-3}$. To achieve a range of leaching volumes, different amounts of water were applied at each irrigation event; 11, 121, 244 and 488 mL for the control (efficient irrigation), low, medium, and high irrigation volumes respectively. The total leaching volume after three weeks (end of experiment) in the 100 $mg·L^{-1}$ N treatments was 384, 661, 982, and 2910 mL/pot in the control, low, medium, and high irrigation and 1128, 1568, 2030, and 3064 mL/pot in the control, low, medium, and high irrigation in the 200 $mg·L^{-1}$ N treatments, respectively. Shoot dry mass more than doubled as fertilizer concentration increased from 100 to 200 $mg·L^{-1}$ N, regardless of the irrigation volume. No difference in shoot dry mass was observed among the irrigation treatments. The 200 $mg·L^{-1}$ N concentration resulted in more leaching than the 100 $mg·L^{-1}$ N.

Because the plants grown with 200 mg·L^{-1} N were larger and needed more water to sustain their growth, they were irrigated more often, resulting in larger leaching volumes. Contrary to our hypothesis, this study provided no proof that fertilizer rates can be reduced when more efficient irrigation practices are used. However, even reducing just the volume of irrigation water applied, without decreasing the fertilizer concentration, will reduce the amount of fertilizer applied, thus reducing production costs and decreasing the risk of environmental pollution.

Additional index words: *Petunia × hybrida*, drip irrigation, leachate, soil moisture sensors, substrate moisture content

Introduction

Container production depends on irrigation and fertilization to grow high quality crops. Container production can be intensive, with high density crops and heavy use of fertilizer and water (Voogt, 2005). Without proper irrigation management, this can lead to leaching and loss of nutrients as runoff into the environment (McAvoy et al., 1992). Plants typically are grown in relatively small containers, resulting in a small root zone. The highly porous soilless substrates used in container production need frequent irrigation, which encourages nutrients leaching (Chen et al., 2001; Majsztrik et al., 2010). Chances of leaching are further encouraged by the frequent, and often excessive, irrigation and higher fertilizer rates used to grow crops. Excessive irrigation is common among US growers due to a lack of knowledge about crop water requirements and irrigation systems controlled by timers (van Iersel et al., 2011)

Fertigation has long been used to improve crop quality in greenhouse and nursery production systems. However, current levels of nutrients used to grow crops are no longer sustainable. Significant amounts of nitrogen and phosphorous applied to crops are either not taken up or leached from the substrate (Colangelo and Brand, 2001; Ristvey et al., 2007). Increasingly strict laws and regulations require US growers to prevent or minimize nutrient leaching and runoff from their facilities. Although capturing and reusing runoff is an option, the required infrastructure can be expensive to install and operate and may lead to the spread of pathogens and crop loss (Hong et al., 2003). As a result, many greenhouses currently do not capture their runoff.

Water and fertilizer interact in multiple ways in container plant production: 1) since fertilizer is commonly added to the irrigation water, excessive irrigation may result in high fertilizer application rates, 2) excessive watering can also leach nutrients from the containers, 3) movement of nutrients in the substrate is by mass flow or diffusion, and thus dependent on θ, and 4) plant water uptake, and thus mass flow of nutrient solution to roots also depends on θ. Our previous research showed up to 83% reduction in water use and reduced nutrient leaching with efficient irrigation control (van Iersel et al., 2009). Thus, we hypothesized that if leaching is minimized through efficient irrigation techniques, high quality plants can be grown with lower fertilizer rates. The objective of this experiment was to quantify the interactive effect of fertilizer concentration and irrigation volume on leaching and growth of petunia (*Petunia × hybrida*) and determine whether growers can use lower fertilizer rates and reduce production costs if they irrigate more efficiently

Materials and Methods

Plant material. Plants were grown in a glasshouse at the University of Georgia. Petunia 'Apple blossom' seedlings were transplanted into 15 cm pots filled with soilless substrate (80% peat, 20% perlite; Fafard 1P; Fafard, Agawam, MA, USA). The pots were watered by hand for 5 d after transplanting to establish adequate roots in the substrate. Subsequently, the plants were irrigated using an automated drip irrigation system throughout the 3-week experiment.

Treatments. Plants were irrigated with fertilizer solution containing 100 or 200 $mg{\cdot}L^{-1}$ N, by injecting water-soluble fertilizer (15N–2.2P–12.5K, 15-5-15 Cal-Mag special, Everris, Dublin, OH, USA) using fertilizer injectors (Dosatron D14MZ2 - 14 GPM, Clearwater, FL, USA). This resulted in an EC of 1.12 and 2.45 $dS{\cdot}m^{-1}$ for the 100 and 200 $mg{\cdot}L^{-1}$ N fertilizer solutions, respectively. Irrigation was controlled using a soil moisture sensor-controlled drip irrigation system, similar to the one described by Nemali and van Iersel (2006). θ was measured using capacitance sensors (EC-5, Decagon Device, Pullman, WA, USA) connected to a datalogger (CR10, Campbell Sci., Logan, UT, USA). The datalogger opened an irrigation valve when the measured θ in a plot dropped below 0.45 $m^3{\cdot}m^{-3}$. There were four irrigation treatments: in the control treatment, plants were fertigated for 20 s using 2 L/h emitters, resulting in minimal leaching. Plants in other treatments were fertigated for 220 s, using 2, 4, or 8 L/h emitters, resulting in irrigation volumes of 11, 121, 244 and 488 mL per irrigation event in the control (efficient irrigation), low, medium, and high irrigation volume treatments, respectively. The goal of these different irrigation volumes was to get different amounts of leaching.

Data Collection. Substrate moisture content readings were averaged by the data logger every 2 h. Leachate from the pots drained into 4 L containers and was collected and quantified weekly. Shoot dry mass was measured at the end of the experiment after drying at 75-80 °C.

Experimental Design and Data Analysis. The experiment was set up as a completely randomized split plot design with fertilizer concentration (100 and 200 mg·L^{-1} N) as the main plot and irrigation treatment (control, and low, medium, and high leachate volumes) as the split. Each treatment was replicated four times, with four pots per experimental unit. All the data were analyzed using ANOVA with Tukey's HSD mean separation using SAS (SAS Institute, Cary, NC, USA).

RESULTS AND DISCUSSION

Irrigation and substrate water content. The irrigation system maintained θ at or above the irrigation threshold (0.45 m^3·m^{-3}) during the entire growth cycle (Fig.1). The control treatment maintained θ close to the threshold, while the θ in the other three treatments rose sharply following irrigation. As expected, the θ increased more in treatments that received more water (Fig.1). The control treatment did show signs of water stress, which was consistent with our previous findings (van Iersel et al., 2010).

Leaching volume. Total leaching volume depended on both the irrigation treatment, as well as the fertilizer concentration: 384, 661, 982, and 2910 mL/plant in the control, low, medium, and high irrigation volumes and 100 mg·L^{-1} N treatments and 1128, 1568, 2030, and 3064 mL/plant in the control, low, medium, and high irrigation volumes and 200 mg·L^{-1} N treatments, respectively (Fig.2). Leaching was higher with the 200 mg·L^{-1} N concentration, likely because the plants grew faster and thus used more water, resulting in more frequent fertigation and increased leaching. This phenomenon was also reported in geraniums (Ku and Hershey, 1992). Frequent irrigation result in high leaching rates, even if the leaching fraction (volume leached/volume applied) remains unchanged (McAvoy et al., 1992).

Shoot dry mass. Shoot dry mass more than doubled as fertilizer concentration increased from 100 to 200 mg·L^{-1} N (45 and 105 g/plant), regardless of the irrigation or leaching volume. No difference in shoot dry mass was observed among the four irrigation treatments (Fig.3) within the same level of N fertilization. The similarity in shoot dry mass among the irrigation treatments might be because the θ threshold (0.45 m^3·m^{-3}) maintained throughout the experiment was high enough to provide sufficient plant available water. Leaching volume also did not affect shoot dry mass. Because the plants were fertigated, leached nutrients got replenished during irrigation. Leaching would be more likely to affect shoot growth when controlled release fertilizer, rather than water soluble fertilizer is used, because leached nutrients would not be replaced.

CONCLUSIONS

The higher fertilizer concentration (200 vs. 100 mg·L^{-1} N) resulted in larger plants, regardless of irrigation and leaching volumes. This suggests that the optimal fertilizer concentration for maximizing growth is independent of the irrigation and leachate volume when plants are fertigated. The larger plants had greater water use and thus needed more frequent irrigation to replenish the used water. Both large irrigation volumes and more frequent irrigation increases leaching if θ is close to container capacity. We did not find evidence to support our hypothesis that fertilizer concentrations can be reduced with more efficient irrigation practices. However, inefficient irrigation results in higher water use and thus increases the amount of fertilizer applied. Efficient irrigation may not lead to a decrease in the concentration of the fertilizer solution required for rapid growth, but can reduce the amount of water, and thus fertilizer that is needed.

Acknowledgements

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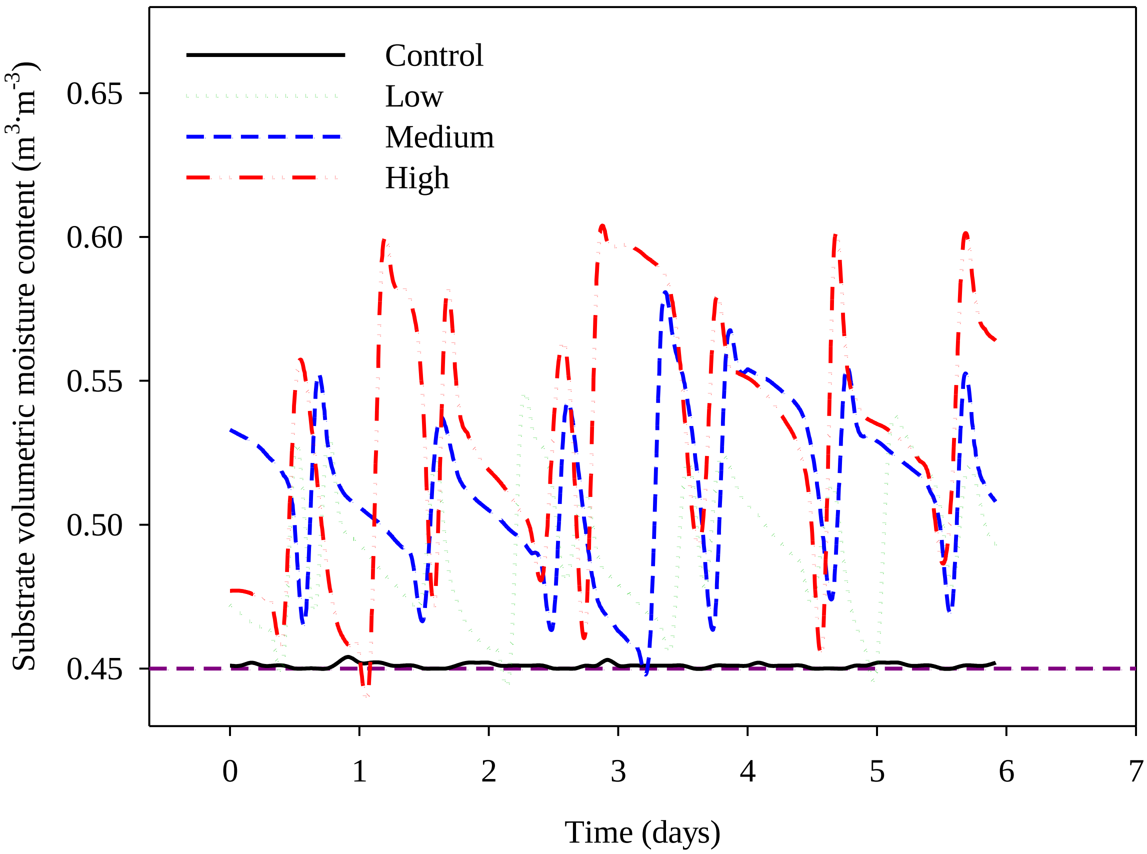

Fig.4.1. Substrate water content as maintained by a moisture sensor-controlled irrigation system. Plants were irrigated when the substrate water content dropped below 0.45 $m^3 \cdot m^{-3}$ (dashed horizontal line). Data were collected at 2 h intervals over a one week period from plants fertigated with 200 $mg \cdot L^{-1}$ N in the fertilizer solution. Control plants were irrigated frequently, but with small amounts of water, while the low, medium, and high treatments were designed to result in increasing amounts of leaching.

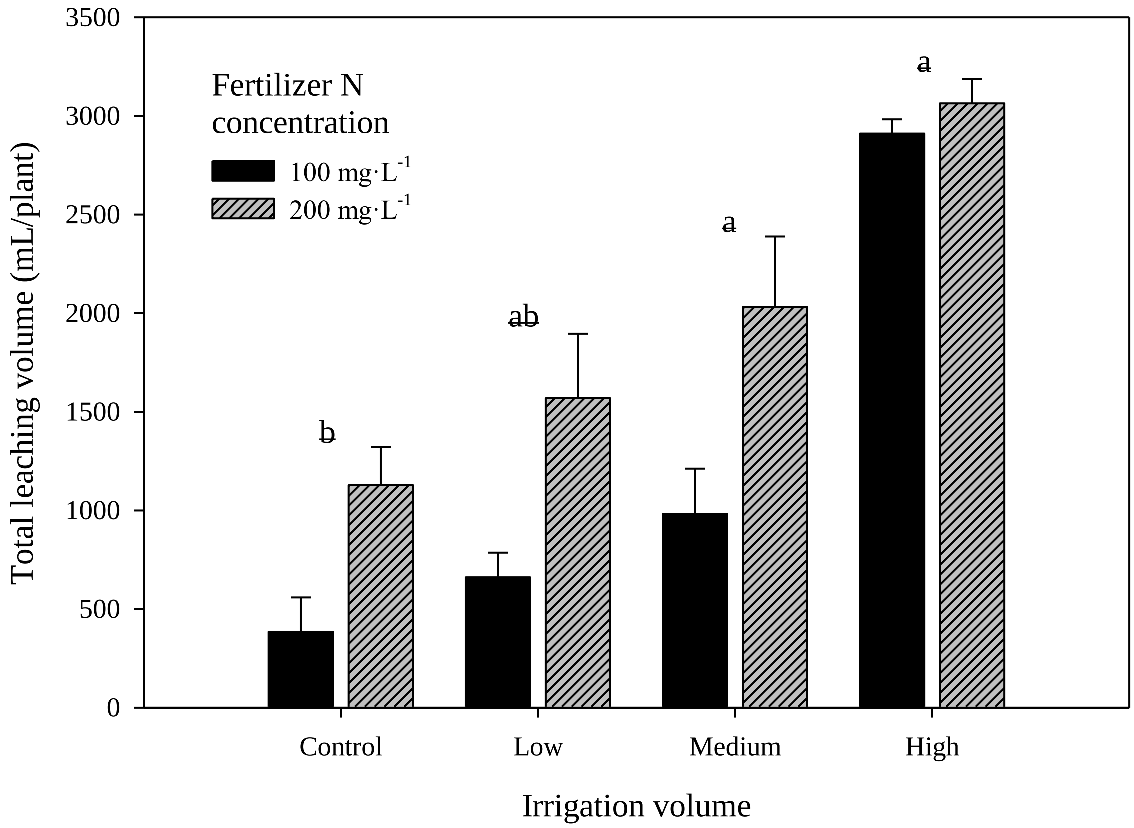

Fig.4.2. Total leaching volume at different irrigation volumes (low, medium & high) and two fertilizer rates (100 and 200 mg·L^{-1} N). Bars (mean ±SD) with the same letters are not significantly different. The letters indicate significant difference among irrigation treatments. 200 mg·L^{-1} N fertilizer resulted in more leaching than 100 mg·L^{-1} N *(P= 0.02*)

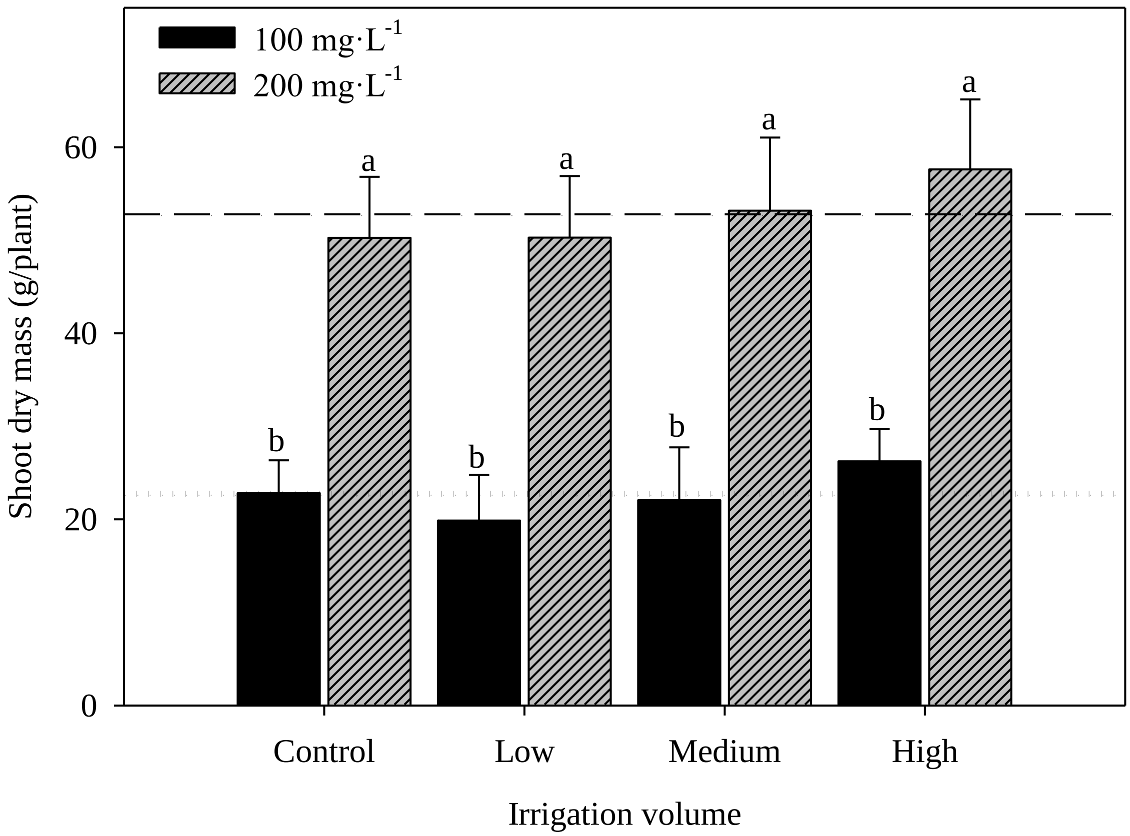

Fig.4.3. Mean shoot dry mass of petunias fertigated with fertilizer solution containing 100 or 200 mg·L^{-1} N, and irrigated efficiently (control) or with different amounts of leaching (low, medium or high). Bars (mean ± SD) with the same letter are not significantly different.

CHAPTER 5

USE OF CONTROLLED WATER DEFICIT TO CONTROL POINSETTIAS HEIGHT

Alem, O. P., P. Thomas and M.W. van Iersel. To be submitted to *HortScience*

Abstract

Production of poinsettias (*Euphorbia pulcherrima*) involves intensive use of plant growth regulators (PGR) to control height. Height control is necessary for visual appeal and post-harvest handling. Growth regulators are relatively expensive and do not always provide consistent height control. Since turgor potential drives cell elongation, and thus stem elongation, drought stress has potential for regulating plant height. Using soil moisture sensor-controlled irrigation, the severity of drought stress can be both monitored and controlled. The objective of our study was to compare poinsettia height control using PGRs (spray, mixture of B-Nine and Cycocel at 1000 mg·L^{-1} and drench, 0.25 mg·L^{-1} Bonzi) to the use of controlled water deficit (WD). Graphical tracking of plant height, using a final target height of 43.5 cm, was used to determine when to apply PGR or controlled WD. In the WD treatment, substrate water content (θ) was reduced from 0.40 to 0.20 m^3·m^{-3} when height exceeded the target height. Plant growth regulators applications (spray or drench) reduced poinsettia height below the final target level of 43.5 cm. Water deficit resulted in an average height of 44.5 cm, closest to the target height, while control plants were taller (49.4 cm). There was no effect of drenching or water deficit on bract size, while spraying PGRs reduced bract size. As compared to the WD and PGR drench treatments, the PGR spray treatment reduced bract size by about 40%. Bract chroma was not affected by WD or PGRs treatments. There was no difference in shoot dry mass between PGRs and WD treated plants. Lateral growth was reduced by the PGR treatments, but not by WD. These results indicate that controlled WD can control poinsettia height.

Additional index words. Bracts, controlled water deficit, height tracking curves, plant growth retardant, substrate volumetric water content

Introduction

Poinsettia is an important seasonal holiday ornamental plant (Snipen et al. 1999; Kannangara and Hansson, 1998). Poinsettias are one of the most economically valuable pot plants in the US and around the world (USDA NASS, 2011; Trejo et al., 2012). In 2009, poinsettias had a wholesale value of over $153 million in the United States (U.S. Department of Agriculture, 2009). Production of high quality poinsettias involves proper fertilization, irrigation, as well as height regulation (Argo and Biernbaum, 1995; Newman and Tant, 1995). Height control is important for production of marketable, compact poinsettias (Fisher and Heins, 1995; Heins et al., 1999; Black and Schoellhorn, 2002). Poinsettia height control is also important for transportation and post-harvest handling (Karlovic et al., 2004; Niu et al., 2002). Tall plants occupy more space and are harder to transport than shorter plants (Hayashi et al., 2001). Optimal poinsettia height may vary depending on cultivar, intended use, or grower/consumer preference. To control poinsettia height, growers often use PGRs (Marosz and Matysiak, 2005; Banon et al., 2002) to control stem elongation. Plant growth retardants are also used to influence flowering, lateral branching (Hayashi et al., 2001), and postharvest quality (van Doom and Woltering, 1991). Plant growth retardants reduce stem elongation by antagonizing or inhibiting biosynthesis of gibberellins (Lodeta et al., 2010; Brown et al., 1997; Rademacher, 1989).

Though effective at suppressing elongation, use of PGRs also has disadvantages. Apart from adding to the cost of production (Mata and Botto, 2009), PGRs are also among the agrochemicals that can contribute to environmental pollution (Berghage and Heins, 1991). Due to their pollution potential, the use of PGRs has restrictions in some countries (Moe et al., 1992a). Regulations limiting PGR use are likely to increase in the future (Clifford et al., 2004). Use of PGRs can also negatively impact plant quality and growth through phytotoxicity (Gibson et al., 2003) and stunting if applied in excess (Hamid and Williams, 1997). Growers face a delicate balance when using PGRs; application of an incorrect rate of PGRs or at the wrong time may lead to irreversible stunting of plants or have no effect on growth (Latimer et al., 2001; Al-Khassawneh et al., 2006; Pritchard et al., 1996). Delayed flowering and reduced leaf and bract size have also been reported with some PGRs in poinsettias (Dicks and Rees, 1973).

There is a need for a safer, more reliable and sustainable means of controlling plant height. Previous work has shown the possibility of controlling plant height by reducing temperature (Berghage, 1989; Moe et al., 1992a; Bakken and Moe, 1995). However, lowering temperature also reduces photosynthesis and metabolic processes, including growth rate, which can delay the crop maturity (Moe et al., 1992b). Other studies have shown that manipulation of light quality can be used to control poinsettia growth (Mata and Botto, 2009; Cockshull et al., 1994). However, manipulating light in greenhouses where poinsettias are grown is difficult and expensive. Being a photoperiodic crop, in addition to photoperiod control, current poinsettia production protocol also utilizes natural seasonal changes in light and day length to grow the plants from rooted cutting to flowering and bract color development. Many growers often start transplanting around early August to get plants ready for the end-of-year holiday market.

The use of water deficit (WD) to control plant growth is not new (Hendriks and Ueber, 1995). However, it has been difficult for growers to control the severity of WD, and thus the impact on growth. If the WD is not severe enough, there may be little impact on stem elongation, while severe levels of WD can negatively impact plant quality. With the advent of precision irrigation systems, such as those controlled by soil moisture sensors (O'Meara et al., 2013; Chappell et al., 2013), there is a potential for successful use of controlled WD to control stem elongation. Such irrigation systems can maintain specific substrate water content (θ) to impose a controlled WD. Application of WD to control stem elongation is based on the role of water in cell expansion and growth. Water is needed for turgor pressure, which drives leaf expansion and stem elongation (Singh et al., 2000; Frensch and Hsiao, 1994). Reductions in growth due to drought stress may also occur as a result of changes in cell wall expansion properties (Neumann, 1995; Cramer and Bowman, 1991). Cell expansion declines under water stress, and as a consequence, leaf expansion and stem elongation decrease with decreasing θ (Sharp, 2002). Hence, regulated WD can be used to control plant height (Cameron et al., 2006). This technique is inexpensive and not likely to cause plant damage if managed carefully. In addition, using WD for plant height control is environmentally friendly and eliminates potential pollution caused by PGRs. Plants grown under controlled WD may also be more acclimated to survive stressful post-harvest handling and conditions (Cameron et al., 2008).

We chose poinsettias as the model species to control stem elongation using WD because graphical tracking curves can be used to determine whether a crop is likely to reach its target height (Fisher and Heins, 2002; Harwood and Hadley, 2004). Graphical tracking can also be used to determine when stem elongation control is needed. Plant height is measured regularly and plotted on the height tracking curves to compare with the expected height at a particular date. When plant plants are taller than expected, then height control is carried out, either through application of PGR or WD. A successive measurement is taken to confirm if the height regulation technique has worked. If the plants are still tall, then another round of height regulation mechanism can be applied. This can be a repeated until a desired height is achieved.

The objectives of this experiment were to 1) test whether controlled WD can be used to control poinsettias height, 2) determine the effect of WD on quality characteristics such as bract color and size, and 3) compare the effects of WD on plant quality to those of PGRs.

Materials and Methods

Plant material. Poinsettia 'Classic Red' cuttings, rooted in Oasis foam blocks (Smithers-Oasis, Kent, OH) were obtained from a commercial greenhouse on the August 4, 2011 and transplanted into 15-cm pots filled with peat:perlite (80:20 v:v) substrate (Fafard 1P; Fafard, Agawam, MA). Controlled release fertilizer (Osmocote 14-14-14, The Scotts Co., Marysville, Ohio; 14N:6.1P:11.6K) was incorporated into the substrate at a rate of 7.7 $g \cdot L^{-1}$ before transplanting. Plants were watered by hand for 10 d until sufficient root development was achieved. Two weeks after transplanting, plants were sprayed with an insecticide (Talus® 40SC-SePRO Corporation Carmel, IN, U.S.A.) and drenched with a mixture of imidacloprid (Marathon 60 Wettable Powder; OHP, Mainland, PA) and dinotefuran (Safari 20 SG; Valent USA Corporation, Walnut Creek, CA) to control whitefly.

Hand irrigation was stopped two weeks after transplanting and a sensor-controlled irrigation system was used to maintain θ at 0.40 $m^3 \cdot m^{-3}$, except in the WD treatment where θ was alternated between 0.40 and 0.20 $m^3 \cdot m^{-3}$. The irrigation system design was similar to that of Nemali and van Iersel (2006). Two capacitance sensors (EC-5; Decagon, Pullman, WA) connected to a datalogger (CR10, Campbell Scientific, Logan, UT) were inserted in the substrate of representative pots in each plot (a group of six plants irrigated with one solenoid valve). The soil moisture sensors were measured every 10 min using a 2.5 VDC excitation voltage supplied by the datalogger. The θ readings were used to control irrigation. Irrigation was triggered by the datalogger if the measured θ was below the thresholds (0.40 $m^3 \cdot m^{-3}$ or 0.20 during WD application). Plants were pinched (apical meristem removed) 33 d after transplanting to a height of 21.6 cm (measured from the base of the bench) to encourage branching and development of compact plants (Faust and Heins, 1996; Berghage et al., 1989; Black and Schoellhorn, 2002). Five to seven nodes were left to develop into branches.

Treatments. Final target plant height was set at 43.5 cm. Pinching height (21.6) and the final target height were entered in an Excel spreadsheet (Department of Environmental Horticulture, University of Florida, Gainesville, FL) to develop sigmoid growth tracking curves that were used to monitor plant height. The data generated two sigmoid curves; upper and lower limit curves that defined the ideal plant height range at any given date. Plant height measurements taken over the course of the experiment were plotted on the growth tracking curves.

Control plants were maintained at a θ of 0.40 $m^3 \cdot m^{-3}$ for the entire experiment, with no PGR application. Substrate volumetric water content was also kept at 0.40 $m^3 \cdot m^{-3}$ in the two PGRs treatment (spray and drench). However, in the spray treatment, plants were sprayed with 1000 $mg \cdot L^{-1}$ of PGRs, a mixture of 85% daminozide (B-Nine, OHP, Inc., Mainland, PA) and 11.8% chlormequat chloride (Cycocel, OHP, Inc., Mainland, PA). The drench treatment received 100 mL of 0.25 $mg \cdot L^{-1}$ paclobutrazol (0.04% paclobutrazol) applied to the substrate (Bonzi, Syngenta Crop Protection, Greensboro, NC). Applications of PGRs were made when the plant height exceeded the upper limit of the growth tracking curves. In the WD treatment, θ was maintained at 0.40 $m^3 \cdot m^{-3}$ when plant height was within the growth curve range. However, when plant height exceeded the upper limits of the expected height range, the plants were exposed to WD by allowing θ to drop to 0.20 $m^3 \cdot m^{-3}$. Substrate water content was kept at 0.20 $m^3 \cdot m^{-3}$ until plant height was back within the height tracking curve limits.

Data collection. Plant height for the four treatments were measured weekly from pinching to the end of the experiment. At the end of the experiment, three fully-expanded, uppermost bracts were sampled from each plant and their size determined using a leaf area meter (LI3100, Li-Cor, Lincoln, NE). In addition, bract color was measured using colorimeter (XL-20; Gardner Instruments Laboratory, Bethesda, MD). Bract color measurements indicate the chroma (a measure of color intensity). The more positive the values are, the more intense the bract color, with red as the basic color of comparison. The spread of the canopy was approximated by measuring two perpendicular widths at the top of the canopy. To quantify overall shoot growth, the two plants from each plot with soil moisture sensors inserted in their root-zone were harvested at the end of the experiment, dried in an oven at 75-80°C, and weighed for shoot dry weight. Water use throughout the study was recorded by the datalogger, as well as environmental data, including daily light integral (DLI) and photosynthetic photo flux (*PPF*) using a quantum sensor (QSO-sun; Apogee Instruments, Logan, UT) and temperature and humidity using a temperature-humidity probe (Vaisala HMP50, Vaisala, Woburn, MA). The plants were grown for 84 d from pinching to the end of the experiment.

Experiment design and data analysis. The experimental design was a randomized complete block. There were eight blocks, and four treatments (control, WD, PGR spray, and PGR drench). The experimental unit was a group of six plants irrigated with a single solenoid valve. The data were analyzed for block, treatment, and interactive effects using a general linear models procedure (proc GLM, SAS v. 9, SAS Institute, Cary, NC). Mean treatment effects on final plant height, bract size and color, shoot dry mass and canopy spread were separated using Tukey's HSD test ($\alpha = 0.05$). Plant height measurements, taken repeatedly on the same plants, were analyzed using repeated measures (proc MIXED, SAS), with LSMEANS used to separate paired differences in plant height among treatments on different measurement dates.

Results and discussion

Plant height. The rapid initial stem elongation immediately after pinching can be explained by active vegetative growth stage (Pujar et al., 2006). However, compared to the expected plant height as determined by the height tracking curves, plant height in all treatments were taller than expected within 21 d after pinching. To control plant height, PGR treatments both spray and drench were applied on 14 d after pinching. In the WD treatment, θ was lowered to 0.20 $m^3 \cdot m^{-3}$ twice to suppress growth, from 24 to 31 d and from 56 to 60 d after pinching (Fig 1). The second and final PGRs application was done on day 34 after pinching. Plant height showed no difference among treatments in the first 19 d after pinching. Difference in plant height occurred from 30 d (p = 0.02) until the end of the study (p < 0.0001). Plants in that received PGR treatment became shorter than WD treatments. The difference in height persisted to the end of the experiment. Control plants were taller than those in other treatments and were above the target height range during the entire the experiment (Fig. 1). The plant height in PGR treatments dropped below the target range between 50 and 60 d after pinching and did not recover. However, WD treated plants achieved the target height range between 50 and 60 d after pinching and remained within the target range until the end of the experiment (Fig.1).

The final plant height was reduced by the PGRs and WD treatments as compared to the control. Plant growth regulator treatments (spray and drench) resulted in plants that were shorter than the target height range, while the height of plants in the WD treatment was within the target height range at the end of the experiment (Fig. 2). The successful regulation of plant growth through WD supports previous suggestions on the feasibility of using regulated WD to control poinsettia height as an alternative to PGRs application (Röber et al., 1981).

Irrigation and WD application. After hand watering was stopped*,* the automated soil moisture sensor-controlled irrigation system successfully maintained the θ in the control and PGRs treatments close to 0.40 $m^3 \cdot m^{-3}$. The mean θ maintained by the irrigation system in the control and PGR treatments was 0.406 ± 0.003 $m^3 \cdot m^{-3}$ (mean±SD) (Fig.3). The mean θ during WD application was 0.207 ± 0.004 $m^3 \cdot m^{-3}$.

Daily water use. The first week of the study (week of transplanting) recorded no daily water use (DWU) (Fig.4). This was because the plants were hand irrigated, which resulted in θ above the θ thresholds set for the automatic irrigation system, thus no automatic irrigation took place. Generally, DWU increased gradually from transplanting as the plants grew larger to a maximum in late October and decreased thereafter (Fig.4). Daily water use also varied with the irrigation thresholds and irrigation treatment. In the WD treatment, DWU increased when θ was set at 0.40 $m^3 \cdot m^{-3}$ as compared to when the θ was 0.20 $m^3 \cdot m^{-3}$. When WD was applied to control plant height, no irrigation was applied until the substrate dried out to 0.20 $m^3 \cdot m^{-3}$. Minimal irrigation took place during WD period when θ was maintained at 0.20 $m^3 \cdot m^{-3}$. Immediately after the θ threshold was changed back to 0.40 $m^3 \cdot m^{-3}$ to remove WD, the irrigation system irrigated frequently to increase θ back to 0.40 $m^3 \cdot m^{-3}$ (Fig. 4)

Shoot dry weight. Control plants had a larger shoot dry mass, than the WD and PGR-treated plants (Fig. 5). Thus, it seems that practices that suppress stem elongation also reduce overall growth and shoot biomass accumulation. Although plants that were exposed to WD were taller than PGRs treated plants (Fig. 2), both treatments had similar shoot dry mass (Fig. 5). It is not clear why the taller WD treated plants had similar shoot dry mass as PGR-treated plants. One possible reason is that PGR-treated plants may have had thicker stems or more stems with more foliage.

Canopy size. Canopy spread was similar in the control and WD treatments, but lower in the two PGR treatments (Fig. 5). Lateral canopy expansion showed a weak, but significant, correlation (r= 0.43; p = 0.014) with stem elongation. However, canopy size was correlated more strongly correlated with shoot dry mass (r =0.56; p = 0.0008) and bract size (r = 0.46; p = 0.0085). Reduction in canopy size as result of PGR application was contributed by stunted shoot growth.

Bract size. Over the years, breeders have developed poinsettia cultivars with larger bracts than their wild ancestors (Parks and Moyer, 2004) to increase their visual appeal. Bract size was similar for the control, WD, and PGR drench treatments, but lower in the PGR spray treatment (Fig. 5). As compared to WD and PGR drench treatments, bract size of PGR spray treatment reduced by about 40%. The reduction in bract size by the PGR sprays can be considered to be a quality reduction and may make plants less marketable (Niu, 2002). Bract size reduction by PGRs applied as spray might be due to the late 2nd application, after the onset of bract initiation (Barrett, 1996; Fisher and Heins, 1997; Hartley, 1992). It was interesting that controlled WD did not reduce bract size despite the fact that WD reduced stem elongation. Our finding on the effect of WD on bract size is similar to the findings of Nowak and Strojny (2001), who found that drought tress of -50 kPa applied during the vegetative growth stage of poinsettia 'Eckespoint Lilo' did not inhibit growth and development. These results suggest the possibility of controlling poinsettias height through WD without affecting bract size.

Bract chroma. Bracts are the showy part of poinsettias that come in many shapes and colors ranging from red, pink, white and bicolored (Trejo et al., 2012). Color intensity plays an important role in appearance, and thus consumer preference (Goreta et al. 2008). Contrary to previous reports that PGR application can increase bract color intensity (Lodeta et al., 2010), there was no difference in bract chroma among the treatments (Fig. 5). Bract chroma was negatively correlated with plant height (r = -0.54; p = 0.0016). It is not clear why taller plants would have reduced bract color, but a potential cause can be the incident radiation. Tall plants may receive more incident radiation than shorter plant since their canopies are above shorter plant, higher levels of ultraviolet radiation can fade bracts color (Musil et al., 2002, Omori et al., 2000; Salama et al., 2011), it has been reported that bracts absorb more ultraviolet radiation than normal leaves.

Conclusions

Soil moisture sensor-controlled irrigation systems can maintain θ close to desired threshold levels and can be used to apply regulated WD to control poinsettias stem elongation. This was shown to be an effective method for height control. In this study, application of WD to control poinsettias stem elongation did not cause any negative side effects on poinsettia quality. The use of regulated WD can help growers reduce PGR applications and potentially increase their profit margin. There is an increasing consumer preference for reduced chemical use in plant production and plants that have not been treated with PGRs may be preferred by many consumers.

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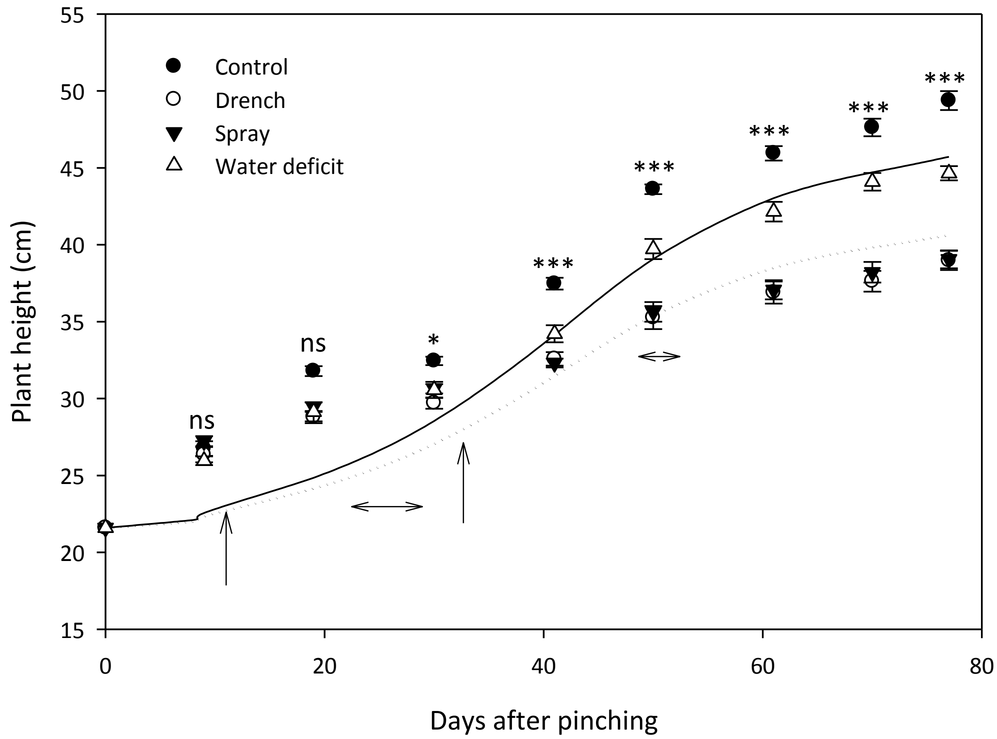

Fig. 5.1. Poinsettia 'Classic Red' height response to plant growth retardant applications (spray or drench) and water deficit treatments as monitored through height tracking curves for 77 d. Growth retardants and WD were applied to control stem elongation, final target height was 43.5 ± 2.5 cm. The vertical arrows indicate PGR applications, while the horizontal arrows indicate water deficit application.

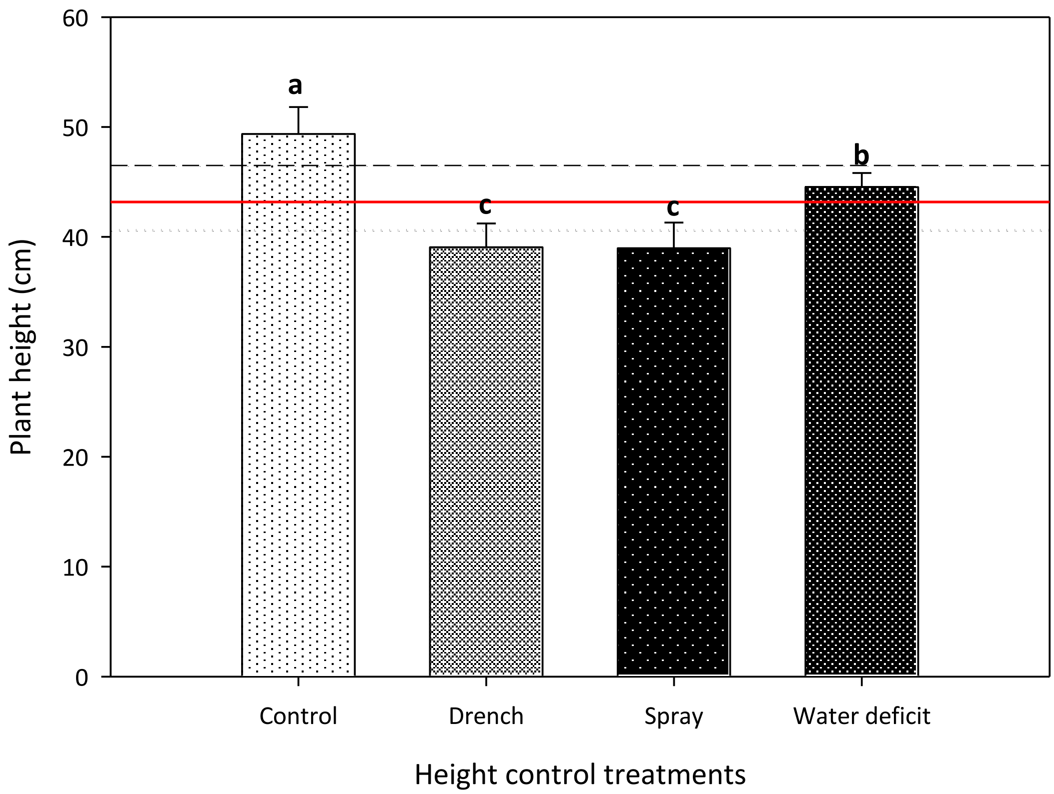

Fig.5.2. The final plant height of poinsettias that were kept well-watered (control), well-watered and treated with spray or drench applications of plant growth retardants, or exposed to two water deficit cycles. Bars (means ± SD) with the same letter are not significantly different according to Tukey's HSD test (α=0.05). The solid horizontal line represents the target height, while the dotted lines represent the limits of the acceptable height.

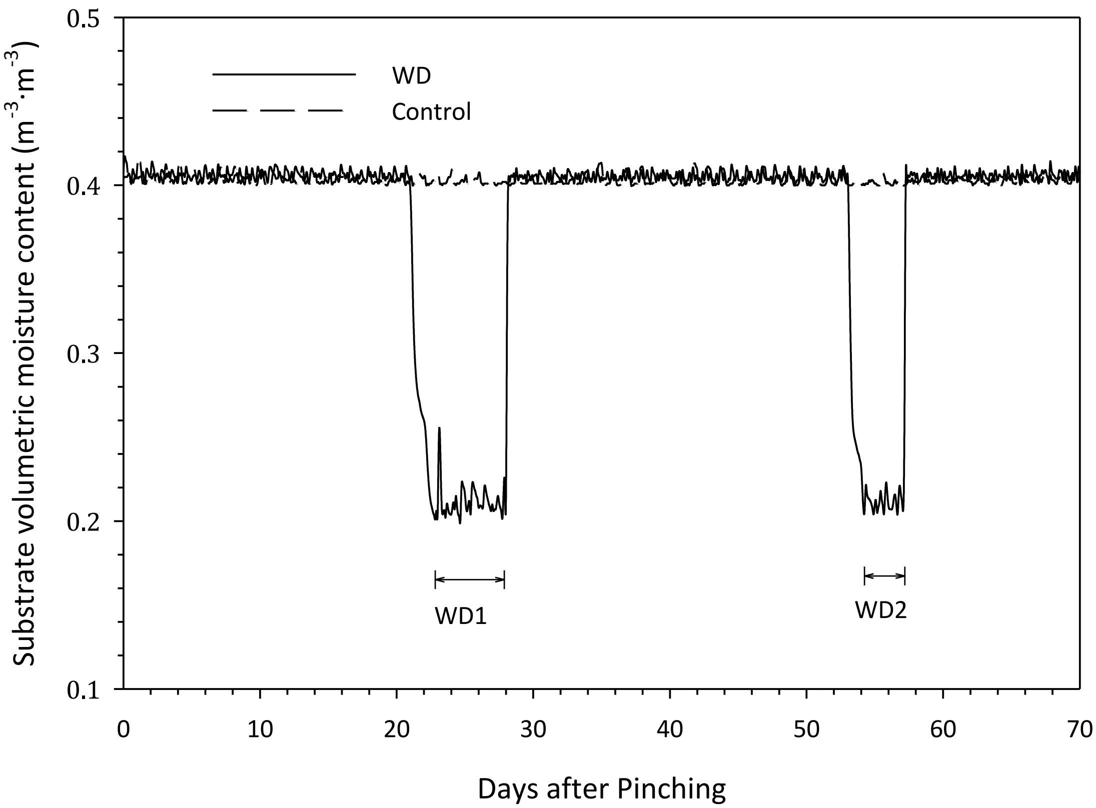

Fig.5.3. Average substrate volumetric water content for one experimental unit of the control and water deficit treatments collected every 2 h. The substrate volumetric water content was maintained at 0.40 $m^3 \cdot m^{-3}$ in the control and the water deficit treatment when growth suppression was not required. The arrows indicate periods when water deficit irrigation (0.20 $m^3 \cdot m^{-3}$) was applied to suppress growth.

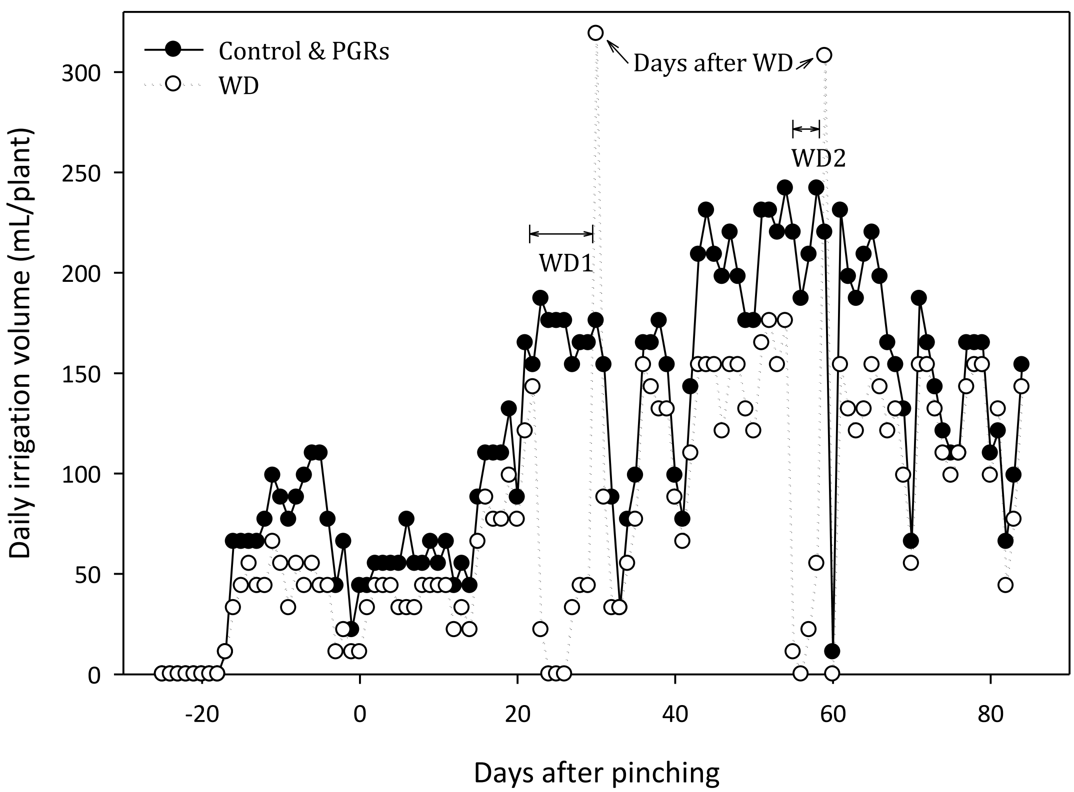

Fig. 5.4. Daily water use of poinsettias in the control [θ of 0.40 $m^3 \cdot m^{-3}$] and water deficit (WD) treatments. In the WD treatments, θ alternated between 0.40 and 0.20 $m^3 \cdot m^{-3}$, depending on plant height. Arrows indicate the periods that the θ set point was decreased to 0.20 $m^3 \cdot m^{-3}$. Peaks in irrigation volume in the WD treatment represent days when the θ set point was changed back to 0.40 $m^3 \cdot m^{-3}$ and the irrigation system applied water frequently to increase θ to 0.40 $m^3 \cdot m^{-3}$.

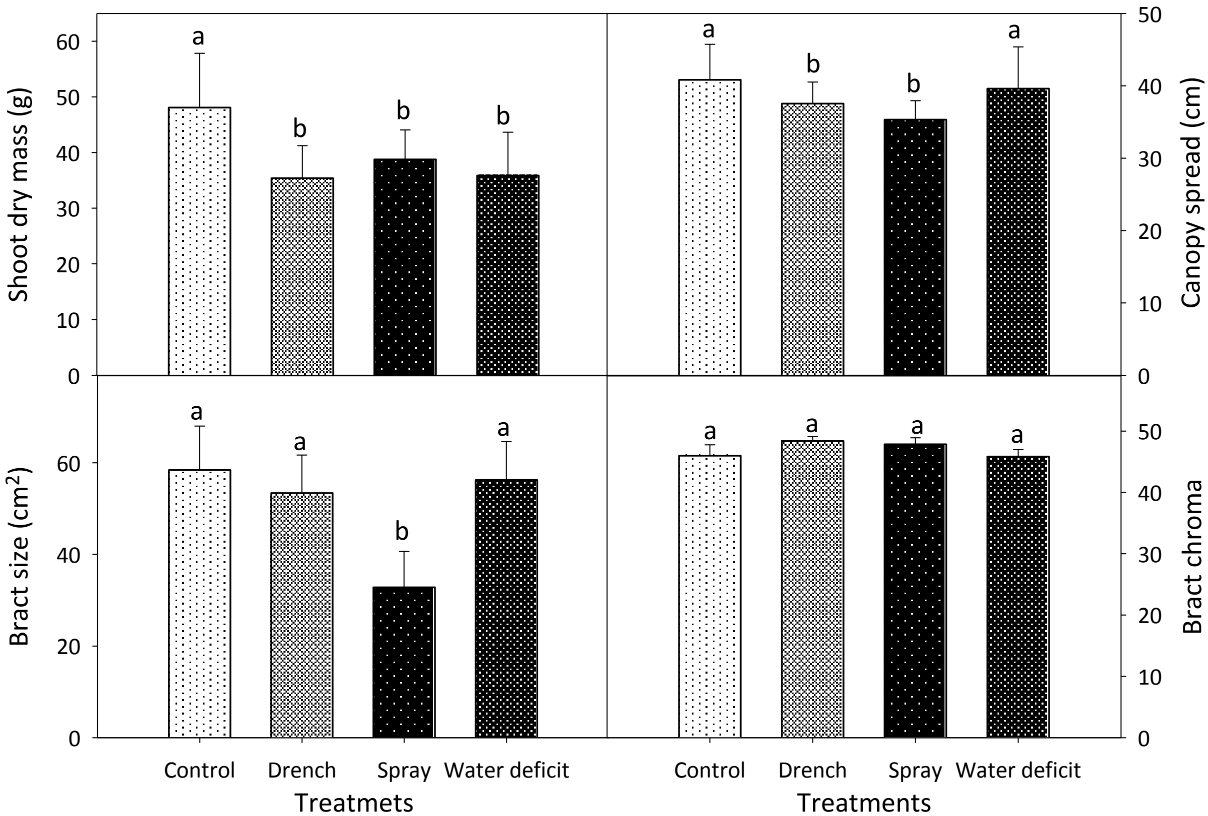

Fig. 5.5. Mean shoot dry mass, canopy width, bract size and bract color of poinsettias treated with plant growth regulator [PGR spray-1000 mg·L^{-1} mix 85% daminozide (B-Nine) and 11.8% chlormequat (Cycocel) and PGR drench-0.25 mg·L^{-1} paclobutrazol)] and water deficit (0.20 m^3·m^{-3}) to control stem elongation. Control plants were kept well watered for entire growing period (0.40 m^3·m^{-3}). Bars (means±SD) with the same letter are not significantly different according to the Tukey's test (α=0.05).

CHAPTER 6

CONTROL OF POINSETTIA STEM ELONGATION BY VARYING SUBSTRATE WATER CONTENT

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Abstract

Height regulation is crucial in poinsettia (*Euphorbia pulcherrima*) production for both aesthetics and postharvest handling. Controlled water deficit (WD) offers a potential alternative to plant growth regulators (PGRs) for poinsettia height regulation. We have previously shown that WD can be used to regulate poinsettia stem elongation. However, it is not clear what the limits are for height control using WD and how it may affect aesthetic qualities, such as bract size. Our objectives were to determine how much shoot elongation can be inhibited using controlled WD and to investigate possible adverse effects of WD on shoot morphology. Rooted cuttings of poinsettia 'Classic Red' were transplanted into 15 cm pots filled with 80% peat: 20% perlite (v/v) substrate. Three target heights (43.2, 39.4 and 35.6 cm) were set at pinching and height tracking curves were used to monitor plants throughout the production cycle. Substrate volumetric water content (θ) was maintained at 0.40 $m^3 \cdot m^{-3}$ (approximately -5 kPa) during well-watered conditions and reduced to 0.20 $m^3 \cdot m^{-3}$ (approximately -75 kPa) when plants were taller than desired based on the height tracking curves. Control plants were maintained at a θ of 0.40 $m^3 \cdot m^{-3}$ throughout the study. Plants with the 35.6 cm target height exceeded the upper limits of the height tracking curve despite being kept at a θ of 0.20 $m^3 \cdot m^{-3}$ for 70 d after pinching and had a final plant height of 39.8 cm. However, the final plant height in the 39.4 and 43.2 cm target height treatments were 41.3 and 43.5 cm respectively, within the 2.5 cm margin of error of their respective target heights. Relative to control plants, bract area was reduced by 53, 47 and 31% in the 35.6, 39.4 and 43.2 cm target height treatments, respectively. Our results indicate that the minimum height that can be achieved using WD is approximately 39-40 cm for this cultivar, but WD may also decrease bract size.

Additional index words. Bracts, controlled water deficit, fertigation, growth tracking curve, plant growth regulator

Introduction

Poinsettia height control involves careful application of height regulation without compromising plant quality. Some important quality traits, such as bract size, bract color, plant height, and form can be jeopardized by height regulation practices, such as PGR application and deficit irrigation. Excessive application of PGRs can result in permanent growth suppression and subsequent stunting of poinsettias as well as reduced bract size (Lewis et al., 2004; Faust et al., 2001; Niu et al., 2002), while application of too little PGR may not sufficiently suppress stem elongation. Similarly, using WD as an alternative means of poinsettia height regulation requires careful management to achieve desired results. Improperly regulated or excessive WD can result in poor quality plants (Liptay et al., 1998). Just like PGRs application, timing of WD application is important for height regulation (Niu et al., 2002). Preferably, height regulation through WD should be employed during vigorous vegetative growth, when the stem elongates most rapidly. In the case of poinsettias, it may not be advisable to apply WD during bract expansion as this may reduce bract size in a similar way as late applications of PGRs (Alem et al., 2014).

The target height of greenhouse crops, including poinsettia, is often determined by market demands or grower preferences (Clifford et al., 2004; Fisher and Heins, 1995; Currey and Lopez, 2011). The desired target height influences how much growth suppression is required during poinsettia growth. While there is a lot of information about the effects of PGR application rate, concentration and frequency (Latimer et al., 1999; Hammond et al., 2007), there is little information about WD as a means of plant height regulation. Drought severity and frequency are known to result in different levels of growth suppression in many species, such as Salvia (*Salvia splendens*), Big bend bluebonnet (*Lupinus havardii*) and petunia (*Petunia*× *hybrida*), (Burnett et al., 2005; Niu et al., 2007; van Iersel et al., 2010). Barrett and Nell (1982) previous study also showed a reduction in poinsettia height with an increase in water stress. Alem et al. (2014) later found that controlled WD can regulate poinsettia height to levels comparable to PGR applications without compromising plant quality. In that study, WD was used to achieve a final target height of 43.2 cm. However, application of WD as a means of plant height regulation has not been popular in the past due to the risk of excessive stress and plant loss. However, in our previous and current studies we have employed precision irrigation techniques to control and apply WD. This automated irrigation system uses soil moisture sensors to monitor and maintain desired θ levels (Nemali and van Iersel, 2006), eliminating risk of excessive drought stress. We hypothesize that desired final poinsettias heights can be achieved by applying different severity and/ or durations of WD. To further test the use of WD as a means of height regulation, the objective of this study was to determine how much growth suppression can be achieved by application of WD and how this affects plant quality.

Materials and Methods

Plant material and growing conditions. Poinsettia 'Classic Red' rooted cuttings were obtained from a commercial greenhouse (Davis Floral, Dewy Rose, GA) on August 7, 2012 and transplanted into 15 cm pots filled with an 80% peat, 20% perlite substrate (v/v) (Fafard 1P; Fafard, Agawam, MA). This cultivar was chosen because of its vigorous growth habit and the resulting need for growth regulation. The plants were fertigated with a water-soluble fertilizer (Peters Miracle Gro Excel 15-5-15 Cal-Mag; 15N–2.2P–12.5K; Scotts, Marysville, Ohio) with a N concentration of 200 $mg \cdot L^{-1}$. Fertilizer solution was injected into a drip irrigation system through a water powered fertilizer injector (Dosatron D14MZ2 - 14 GPM, Clearwater, FL). Plants received fertilizer solution at every irrigation event. This fertilizer was chosen because it has high levels of Magnesium (Mg) and Calcium (Ca) which are important for poinsettia growth (Bierman et al., 1990).

The plants were pinched 27 d after transplanting to a height of approximately 22 cm, leaving five to seven nodes, typical of poinsettias commercial production protocols (Faust and Heins, 1996). Height monitoring was started immediately after pinching using height tracking curves developed with software from the University of Florida, Department of Environmental Horticulture (Gainesville, FL). These tracking curves are developed by entering the pinching date, plant height at pinching, target height and the expected growth duration into the spreadsheet. After pinching, plant height was measured every 2 to 3 d and plotted in the height tracking curves to compare actual height with the expected height at a particular date. When plants were taller than expected, plants were exposed to WD until their height was within the expected range again. A fungicide drench, with a mixture of Subdue maxx (Syngenta, Switzerland) and 3336 (Cleary Chemical Corporation, Dayton, NJ), was applied on Sept. 5, 2012 to control soil-borne pathogens.

Height control. Substrate water content was maintained at 0.40 $m^3 \cdot m^{-3}$ when plant height was within the target range and reduced to 0.20 $m^3 \cdot m^{-3}$ to apply WD when height regulation was needed. A soil moisture sensor-controlled irrigation system, similar to the one described by Nemali and van Iersel (2006) was used to maintain θ at the desired thresholds. The irrigation system was controlled by two capacitance soil moisture sensors (EC-5; Decagon, Pullman, WA) per plot. The two sensors were inserted diagonally in the root-zone of two representative plants in each experimental unit. The capacitance soil moisture sensors were connected to a data logger (CR10; Campbell Scientific, Logan, UT) through two multiplexers (AM16/32; Campbell Scientific). The data logger measured the voltage output from the soil moisture sensors every 10 min using a 2.5 VDC excitation voltage. The voltage readings were then converted to θ using a substrate-specific calibration ($\theta = \text{voltage} \times 1.8862 - 0.5624$, $r^2 = 0.95$). Whenever the average θ fell below the threshold θ (0.40 or 0.20 $m^3 \cdot m^{-3}$ during WD application), the datalogger sent a signal to a relay driver (SDM-CD16AC/DC controller; Campbell Scientific), which opened a solenoid valve (DV, Rain Bird, Azusa, CA) to irrigate the plants for 20 s with 11 mL of water at each irrigation.

Target plant heights were set at 43.2, 39.4 and 35.6 (± 2.5) cm (from the bottom of the pot to the top of plant). Control plants were grown without any height regulation. When the plant height was above the target range as determined by the height tracking curves, θ was reduced to 0.20 $m^3 \cdot m^{-3}$ to apply WD. Substrate water content was kept at 0.20 $m^3 \cdot m^{-3}$ until plant height was within the height tracking curves, after which θ was increased back to 0.40 $m^3 \cdot m^{-3}$.

Data collection. Temperature and relative humidity (RH) were measured at 5-min intervals using a temperature/-humidity probe (HMP50, Vaisala, Woburn, MA), and photosynthetic photon flux (*PPF*, QSO-sun; Apogee Instruments, Logan, UT) was measured every 20 s. The data were used to determine the daily light integral (DLI), and the daily average, maximum, and minimum temperature, vapor pressure deficit (VPD), R.H, and *PPF.* The data logger calculated VPD from R.H and temperature data and the daily light integral (DLI) from *PPF*. Temperature, DLI, and R.H reduced gradually from transplanting to the end of the experiment, while VPD generally increased over time (Fig. 1). The average θ values were recorded by the data logger every 2 h. To determine the relationship between θ and substrate matric potential, a tensiometer with a pressure transducer (T5, UMS, Munich, Germany) was inserted into one pot with a soil moisture sensor in a 43.2 cm target height treatment. Tensiometer data were recorded by the data logger as well. The daily number of irrigations for each experimental unit was recorded and used to calculate the daily and total irrigation volumes in each plot.

Two plants from each experimental unit that had soil moisture sensors inserted in their root-zone were harvested at the end of the experiment, their bracts were detached from the stem and total bract area was determined using a leaf area meter (LI-3100, Li-Cor, Lincoln, NE). The number of nodes and internodal length were measured on the main shoot (the upper most shoot from the point of pinching). The shoots were dried in an oven at 75-80 °C for one week to determine shoot dry weight.

Experimental design and statistical analysis. The experimental design was a randomized complete block with eight blocks and four treatments (3 target heights and a control). Blocking was done to account for environmental gradients that may exist along the greenhouse bench. The experimental unit was a group of four plants irrigated using the same solenoid valve. Data were subjected to analysis of variance (proc GLM, SAS, SAS Institute, Cary, NC). Treatment means were separated using Tukey's HSD.

Results and Discussion

Height tracking. Plant height in the 35.6 cm target height treatment remained above the upper limits of its tracking curve, despite being kept under WD from 8 d after pinching until the end of the experiment. Plants in the 39.4 cm target height treatment exceeded the upper limit of their tracking curve at 8 d after pinching, at which time WD was applied to slow stem elongation. Plant height in the 39.4 cm target treatment remained above the tracking curve limit for 5 week with WD application (Fig. 2B). Thereafter, θ was maintained at 0.40 $m^3 \cdot m^{-3}$ for one week before a second cycle of WD was applied for 7 d. After the second WD application, plant height in the 39.4 cm target height treatment remained within its tracking curve limits until the end of the experiment. Thus, to achieve the target height of 39.4 cm, the plants were subjected to WD for 42 d (50% of the growth duration after pinching). The 43.2 cm target height treatment was subjected to the shortest duration of WD to maintain plant height within the tracking curve limits. Water deficit application in the 43.2 cm target height treatment was started two weeks after pinching for 20 d. Plants were then maintained at 0.40 $m^3 \cdot m^{-3}$ for 18 d before application of a second, 5-d WD cycle. The control plants were the tallest, they grew above the upper limits of the height tracking curve for the highest target height treatment (43.2 cm) during the entire experiment period (Fig. 2D). Similar trends in plant height were maintained until the end of the experiment when final height was measured (Fig. 3). These results suggest that there are limits of which heights can be achieved with WD. For 'Classic Red', this limit is about 39 to 40 cm. 'Classic Red' is considered a vigorous cultivar (Currey et al., 2011), so WD may result in lower heights in less vigorous cultivars.

Irrigation. The drip irrigation system maintained θ close to the thresholds of 0.40 and 0.20 $m^3 \cdot m^{-3}$, sufficient irrigation and WD, respectively. It took approximately 2 d for θ to drop from 0.40 to 0.20 $m^3 \cdot m^{-3}$ upon initiation of WD. There was a close relationship between θ and matric potential throughout the experiment, regardless of environmental conditions or plant growth (Fig.5). Substrate matric potential stayed at approximately -5 kPa when θ was kept at 0.40 $m^3 \cdot m^{-3}$ (Fig.5). At WD initiation, the substrate matric potential dropped gradually between 0.40 – 0.35 $m^3 \cdot m^{-3}$. At these θs, the matric potential ranged from -4 to -14 kPa. However, beyond 0.35 $m^3 \cdot m^{-3}$, the matric potential dropped abruptly, dropping to -36 kPa at 0.24 $m^3 \cdot m^{-3}$ then to approximately -75 kPa as the θ stabilized at 0.20 $m^3 \cdot m^{-3}$. When WD was stopped, the matric potential increased gradually towards -5 kPa as the θ increased from 0.20 to 0.40 $m^3 \cdot m^{-3}$ (Fig.5). The abrupt change in matric potential as the substrate dries out is consistent with previous reports that soilless substrates hold most of the plant available water within a narrow matric potential range (1 to –20 kPa) (Kiehl et al., 1992; Raviv et al., 2002), because of the many large pores in soilless substrates. However, poinsettias still grew at a matric potential of -75 kPa, contrary to previous reports that water in soilless substrates becomes unavailable to plants beyond -20 kPa (Kiehl et al., 1989; Milks et al., 1992; Murray et al., 2004). Earlier studies put the limits of available water at even higher matric potential; de Boodt and Verdonck (1972) classified water held at a matric potential below -10 kPa to be unavailable, although this was not based on plant responses. Plants vary in their response to drought stress and ability to take up water from the soil. Recent studies have also stressed the importance of considering plant species and substrate hydraulic conductance when predicting plant available water (Lobet et al., 2014; O'Meara et al., 2014).

Daily irrigation volume. The daily irrigation volume of the control plants increased from transplanting to 42 d after pinching and declined thereafter as plants matured (Fig. 6). The control plants received more water from the middle to end of the study than the smaller plants with a target height of 43.2 cm. Large differences in daily irrigation volume between control and treatment plants occurred during WD application (Fig. 6). Plants did not get watered during the first 1 to 2 d of WD as the substrate dried out to 0.20 $m^3 \cdot m^{-3}$, after which enough water was applied to maintain θ at 0.20 $m^3 \cdot m^{-3}$. Irrigation volume was low during WD as compared to when θ threshold was set at 0.40 $m^3 \cdot m^{-3}$, suggesting that drought-induced stomatal closure reduced plant water use. On days when WD was ended and the θ threshold reset to 0.40 $m^3 \cdot m^{-3}$, frequent irrigation was needed to raise the θ back to 0.40 $m^3 \cdot m^{-3}$. This resulted in spikes in the irrigation volume (Fig. 6). It took less than a day for θ to increase back to 0.40 $m^3 \cdot m^{-3}$. Daily water use was also affected by environmental variables especially, DLI, generally water use was low on days with low DLI.

Total irrigation volume. The cumulative irrigation volume increased with increasing target height, with control plants receiving the largest total irrigation volume. Total irrigation volume approximately doubled as the target height increased from 35.6 to 43.2 (Fig.7). The 39.4 cm treatment was exposed to WD for 12 d more than the 43.2 cm treatment and this resulted in a 30% reduction in total irrigation volume. Thus, a 30% reduction in total irrigation volume reduced plant height by 5%. The 35.6 cm target height treatment had a 45% reduction in total irrigation water for an 8% reduction in final plant height.

Number of nodes and internode length. The reduction in plant height due to application of WD can either be explained by a reduction in the number of nodes (Pace et al., 1999) or internodal length (Pearson et al., 1995; Carvalho et al., 2002). The number of nodes on the dominant stem of each plant showed no correlation with plant height and inconsistent treatment effects (Fig. 8). Node initiation and development in poinsettias appears to be insensitive to WD. Control plants had longer internodes than WD treated plants. The target height of 43.2 cm resulted in longer internodes than 35.6 and 39.4 cm target heights (Fig. 8). The reduction in internode length with an increase in duration and frequency of WD is not surprising, since WD affects cell expansion (Frensch and Hsiao, 1994; Sharp, 2002), which in turn affects internode elongation. There was a strong relationship between internode length and plant height (Fig. 9).

Shoot dry weight. The reduction in shoot dry weight showed a similar trend as plant height. The two lower target heights treatments, 35.6 and 39.4 cm, resulted in the lowest shoot dry weight, followed by the 43.2 cm treatment, and control plants had the largest shoot dry weight (Fig.

10). Reductions in shoot dry weight at lower θs, similar to the 0.20 $m^3 \cdot m^{-3}$ WD level applied in this study, have been reported in a variety of species, including American alumroot (*Heuchera americana*) (Garland et al., 2012), *Hibiscus acetosella* (Bayer et al., 2013), and petunia (*Petunia* ×*hybrida*) (van Iersel et al., 2010).

Water deficit caused a larger reduction in shoot dry weight than plant height. Shoot dry weight:height ratio was 0.56, 0.55, 0.71 and 0.97 (g/cm) in 35.6, 39.4 43.2 cm target height and control treatments, respectively. Similar results have been reported previously with salvia (*Salvia splendens*) (Burnett et al., 2005). Compared to control plants, there was a 55, 54, and 38% reduction in shoot dry mass and a 22, 19, and 15% reduction in height in the 35.6, 39.4 and 43.2 cm target height treatments, respectively. This suggests that shoot biomass accumulation is more sensitive to WD than plant height. Water deficit may affect a variety of plant growth and morphological features, such as number and size of leaves and canopy density, hence reducing shoot biomass (Niu et al., 2006; Burnett and van Iersel. 2008).

Bract area. Bracts are the main ornamental part of poinsettias and bract area or size can be affected by height regulation practices, such as spray applications of PGRs in the later stages of development (Niu et al., 2002; Currey et al., 2002). Water deficit application reduced bract area of poinsettias and this reduction in bract area increased with an increase in duration of WD application. Relative to control plants, bract area was reduced by 53, 47, and 31% in 35.6, 39.4, and 43.2 cm target height treatments, respectively. Bract area reduction due to WD is not surprising, since bracts are modified leaves and leaf expansion is often affected in the early stages of drought stress (Fernandez et al., 2002).

Conclusions

Application of controlled WD can be used to regulate poinsettia stem elongation. Water deficit suppresses poinsettia stem elongation by reducing the length of the shoot internodes. The frequency and duration of WD application is determined by the desired final target height. The ease of poinsettias height control through WD depends on the target height. However, there are limits to how much height control can achieved; 39-40 cm appears to be the lowest achievable height for 'Classic Red'. Application of WD may also reduce bract area, which is not unexpected given the overall reduction in plant size.

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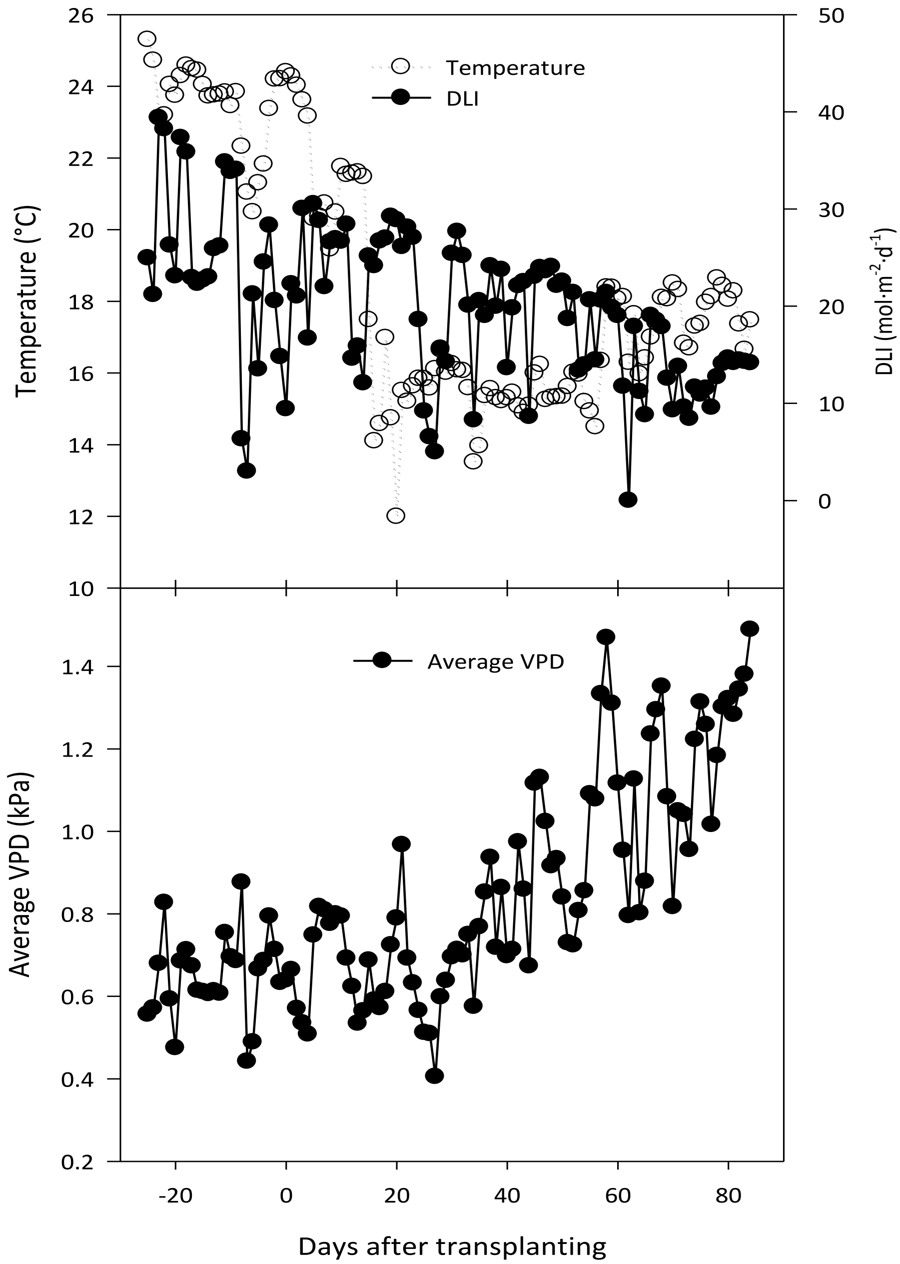

Fig.6.1. Daily light integral and average daily temperature and vapor pressure deficit in the greenhouse from transplanting to the end of the experiment.

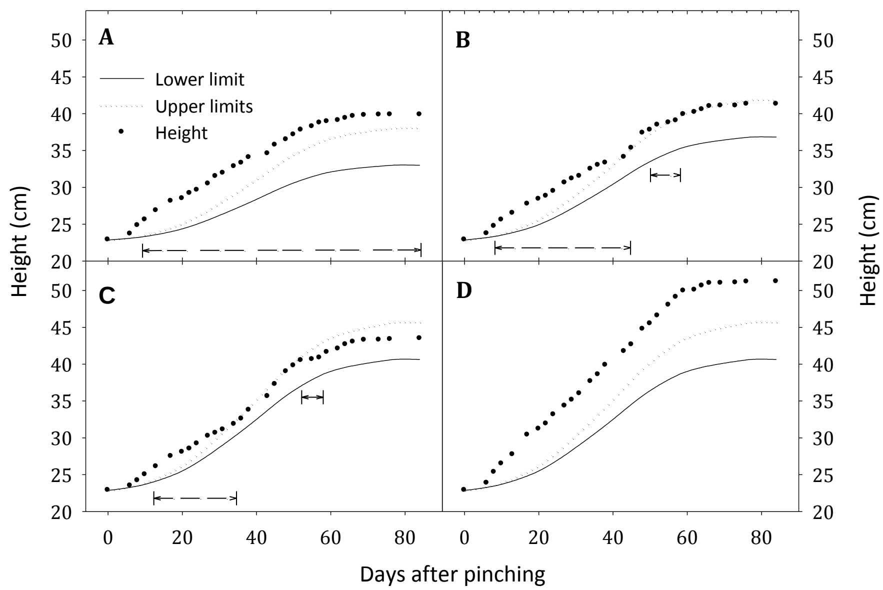

Fig.6.2. Plant height and sigmoidal height tracking curves with 35.6 cm (A), 39.4 cm (B), and 43.2 cm (C) target heights, as well as control plants (D). The upper and lower limits curves are based on final target heights ± 2.54 cm. The control treatment includes height tracking curve for the 43.2 cm target height treatment. Horizontal arrows indicate times the plants were exposed to a water deficit (substrate water content of 0.20 $m^3 \cdot m^{-3}$).

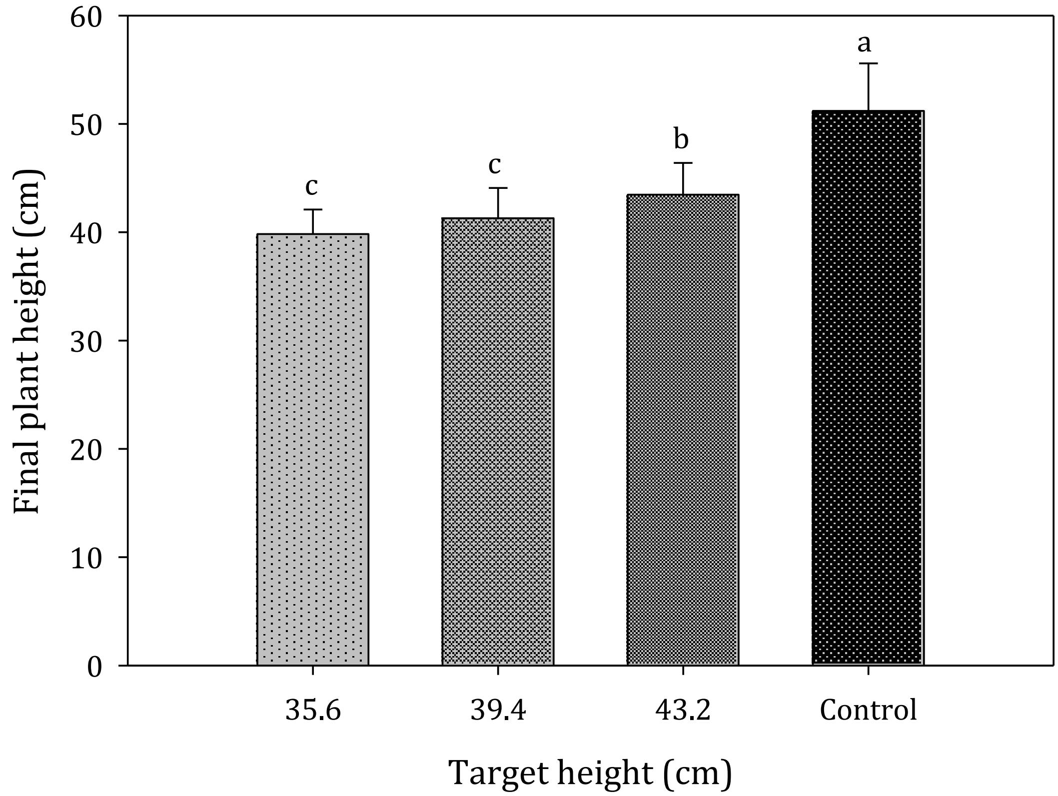

Fig.6.3. Final plant height of water deficit-treated and control plants at the end of the experiment. Bars (means ± SD), with the same letter are not significantly different according to Tukey's test (P = 0.05). Plants with a target height of 35.6 cm were taller than the upper limit of the target height.

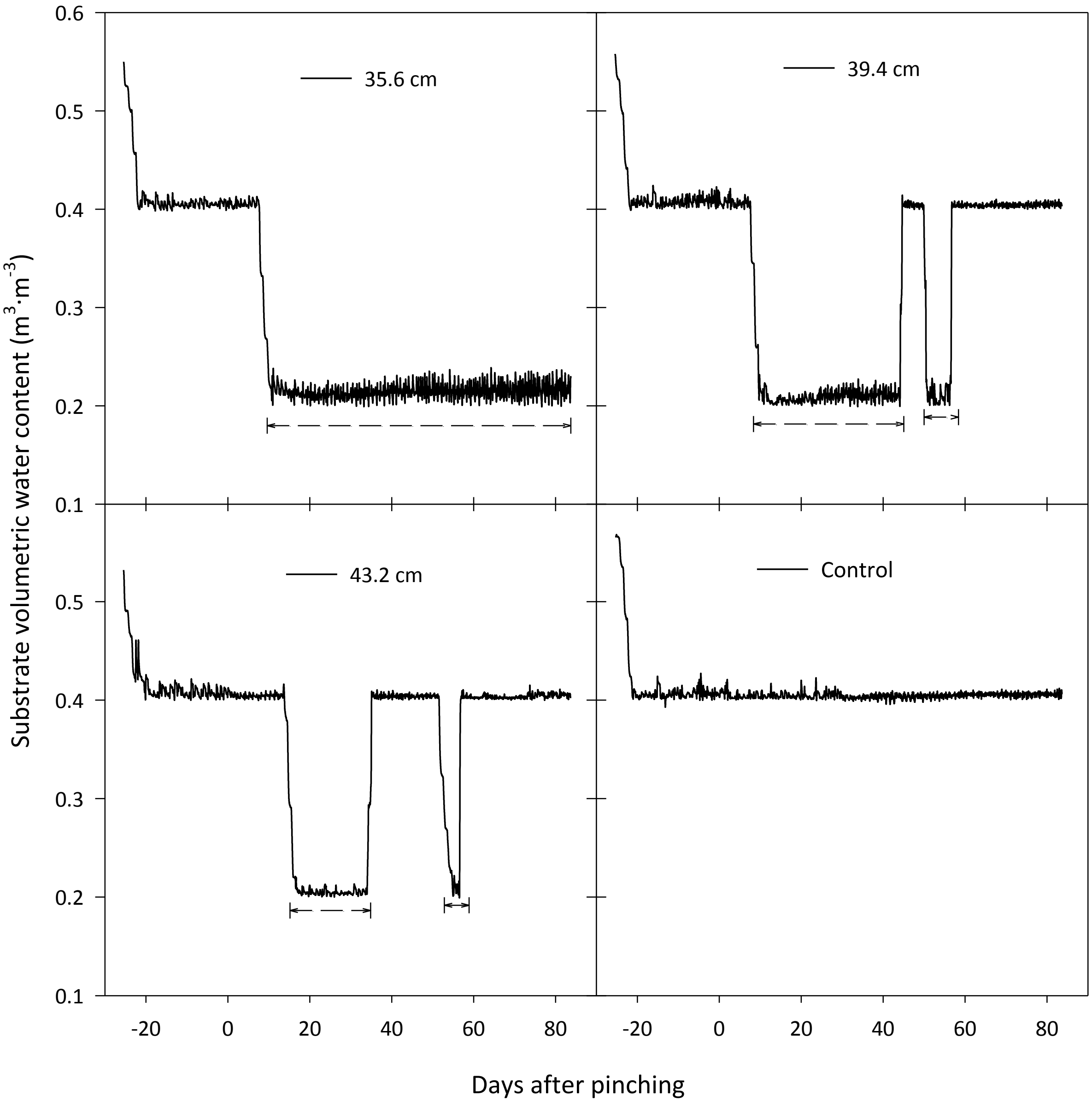

Fig.6.4. Substrate volumetric water content (θ) as maintained by the soil moisture sensor-controlled drip irrigation system in the control, 35.6 cm, 39.4 and 43.2 cm target height treatments. Control plants were kept at a constant θ matric of 0.40 $m^3 \cdot m^{-3}$, while the θ in the other treatments was reduced to water deficit (0.20 $m^3 \cdot m^{-3}$) when height control was needed. Horizontal arrows indicate when water deficit was.

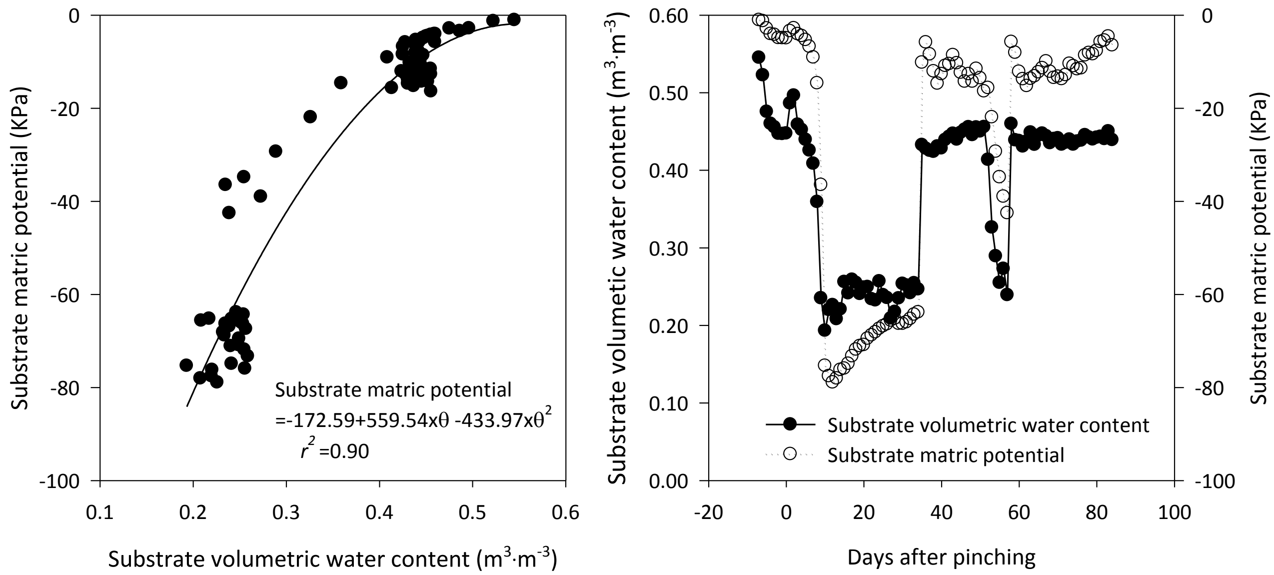

Fig.6.5. The relationship between substrate volumetric moisture content (θ) and substrate matric potential measured in the same pot, as θ was altered between 0.40 and 0.20 $m^3 \cdot m^{-3}$ (left) and substrate volumetric water content and matric potential over 90 d, from 7 d before pinching to the end of the study.

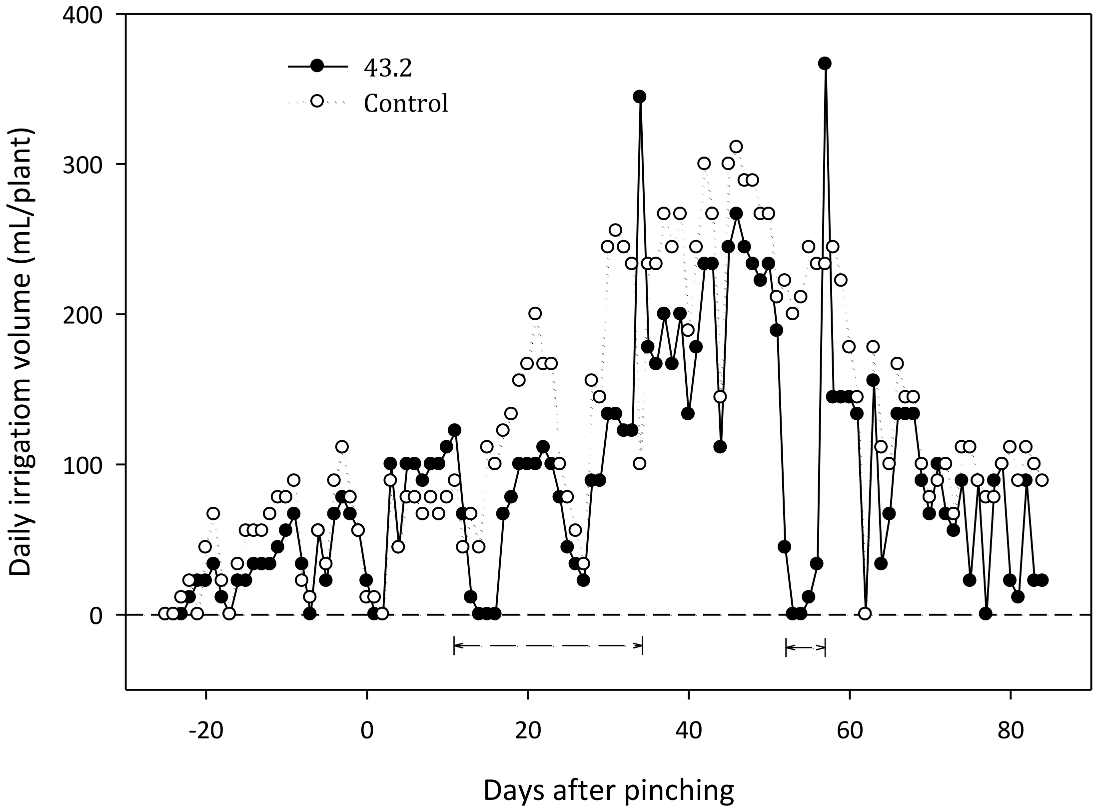

Fig.6.6. Daily irrigation volume of representative plants during sufficient irrigation (0.40 $m^3 \cdot m^{-3}$) and water deficit application. The arrows indicate periods of WD application and the peaks on days 34 and 57 (left) represent days when substrate water content was increased from 0.20 to 0.40 $m^3 \cdot m^{-3}$.

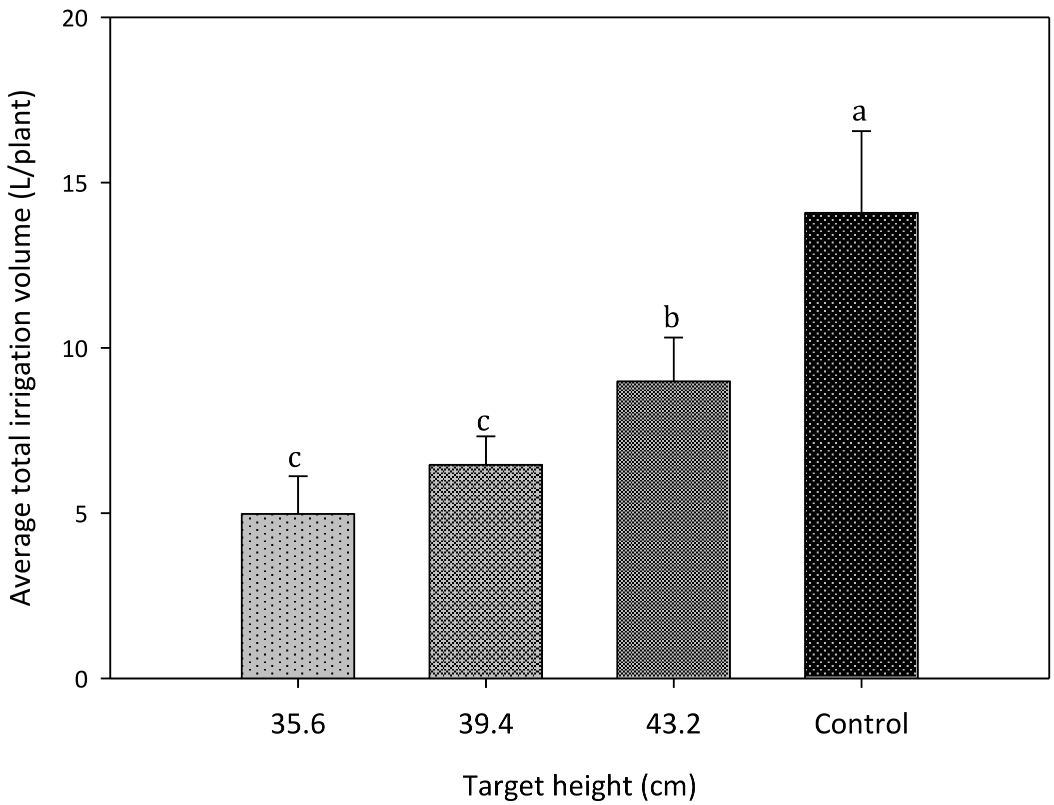

Fig.6.7. Total irrigation volume for poinsettias with different target heights and control plants over the course of the 105 d growing period (from transplanting to the end of the study). Bars (mean ± SD) with same letters are not significantly different (α = 0.05).

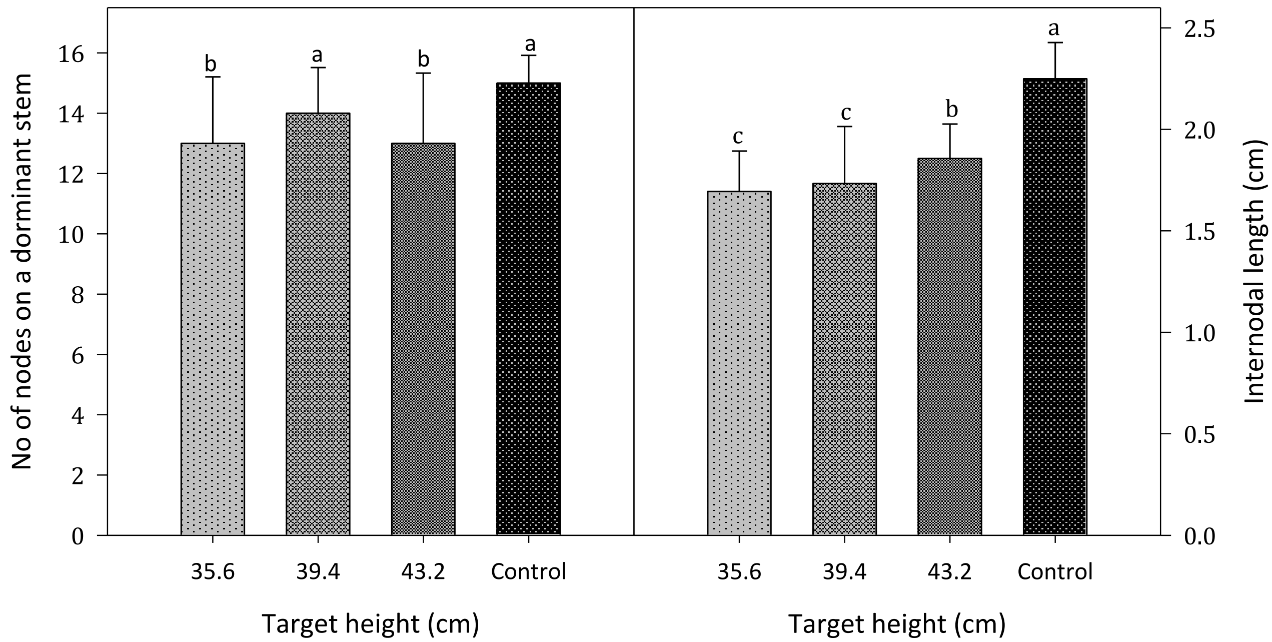

Fig.6.8. The number of nodes (left) and average internode length (right) on the dominant stem of poinsettia. Bars (means ±SD) with the same letter are not significantly different according to Tukey's test (*P* = 0.05).

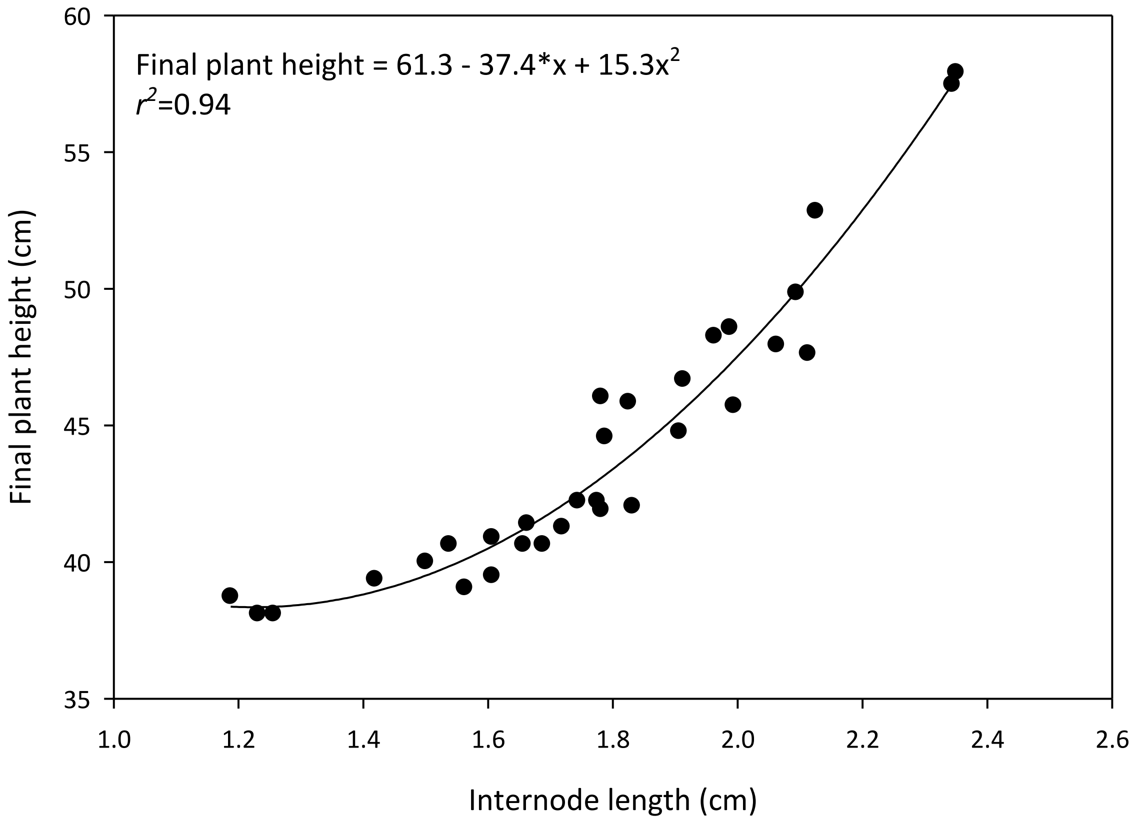

Fig.6.9. The relationship between final plant height and the average internode length measured on a dominant stem of poinsettia. Data from all 32 experimental units are shown.

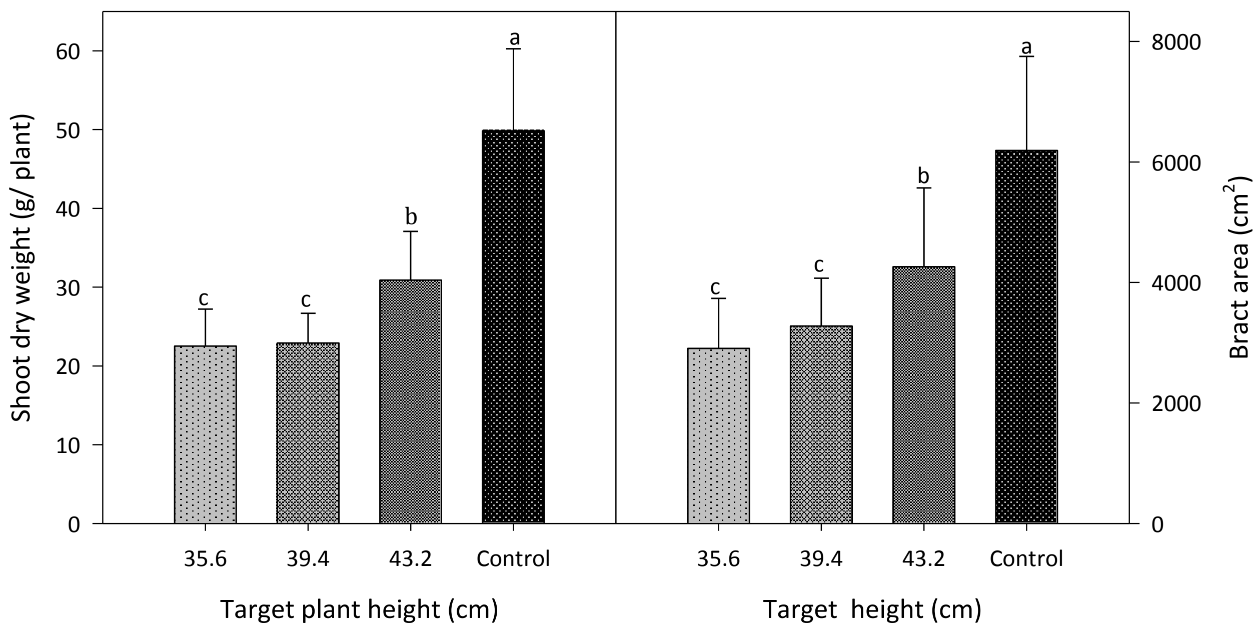

Fig. 6.10. The mean shoot dry weight (right) of plants exposed to water deficit for height control and control plants and their bract area. Bars (means ± SD) with the same letter are not significantly different according to the Tukey's test (P = 0.05).

CHAPTER 7

CONCLUSIONS

Soil moisture sensor controlled irrigation systems can efficiently irrigate plants with minimal or no leaching. Reducing leaching saves fertilizer, water, and decrease environmental contamination of chemical- or nutrient-laden leachate. Lower rate of fertilizers can be used to produce bedding plant crops if efficient irrigation techniques that reduce or eliminate leaching are used. Higher substrate water contents and fertilizer rates result in larger plants that transpire more thus demand more irrigation. However, high fertilizer rates and substrate water content result in reduced flowering. For petunia, lower fertilizer rates and moderate substrate water content result in improved flowering.

Large irrigation volumes and high fertilizer rates encourage leaching in containerized plant production, especially when the substrate water content is close to saturation. Large irrigation volumes can increase substrate water content above container capacity and excess water is lost as leachate. If fertilizer is applied together with irrigation water, leaching due to excessive irrigation can result in nutrient leaching and runoff, resulting in waste of fertilizer without an improvement in plant growth or quality. Frequent irrigation can also increase leaching if substrate water content is close to container capacity. We did not find evidence to support our hypothesis that fertilizer concentrations can be reduced with more efficient irrigation practices. However, inefficient irrigation results in higher water use and thus increases the amount of fertilizer applied.

Controlled WD can be used to regulate poinsettia stem elongation. This technique is made easier and more effective with soil moisture controlled irrigation system. Soil moisture sensor-controlled irrigation systems can maintain substrate water content close to desired threshold levels and can be used to apply regulated WD to control poinsettia stem elongation. Careful monitoring and control of WD through soil moisture sensing eliminates risk of excessive stress that might occur during WD application. The use of regulated WD can help growers reduce PGR input in plant production and potentially increase profit margins. There is an increasing consumer preference for reduced chemical use in plant production and plants that have not been treated with PGRs may be preferred by many consumers. The frequency and duration of WD application is determined by the desired final target height. The ease of poinsettias height control through WD depends on the desired target height. However, there are limits to how much height control can be achieved through WD. For highly vigorous cultivars such as 'Classic Red', the height lowest height limit achievable with WD is 39-40 cm. Application of WD may also reduce bract area, which is not unexpected given the overall reduction in plant size.