ABSTRACT

PREHN, ALISON. A Gravimetric Approach to Real-Time Monitoring of Substrate Water Content in Container-Grown Nursery Crops. (Under the direction of Drs. Stuart L. Warren and Ted E. Bilderback.)

Water management should be the core of container nursery production as it is linked directly to both water and nutrient use efficiency and ultimately environmental impact. Research needs to be conducted in order to discover new ways to be more efficient when irrigating. The goals of this research were: (1) to determine the feasibility of an irrigation controller that relies on real-time monitoring of substrate weight and (2) to determine parameters to make this system more practical and efficient. Two studies were conducted in which the gravimetric technique was used via a load cell/computer interface to determine irrigation scheduling (irrigation volume and time of water application).

The first study was a 2 x 2 factorial. The main factors were two substrates [8 pine bark : 1 sand substrate (PBS) or an 8 pine bark : 1 clay substrate (PBC)] and two irrigation treatments. The irrigation treatments irrigated either at 1200, 1500, and 1800 HR with sufficient volume to return container capacity (CC) to 98% (PBS or PBC PM Replacement) or irrigated to return CC to 98% whenever CC dropped below 94% regardless of time (PBS or PBC On Demand). The study also included two treatments that served as industry controls: a PBS substrate irrigated at 0100, 0400, and 0700 HR (AM 0.2 LF) or at 1200, 1500, and 1800 HR (PM 0.2 LF). The industry control treatments were maintained at a leaching fraction (LF) of 0.2. *Cotoneaster dammeri* ‘Skogholm’ was used in all treatments. The substrate × irrigation interaction was not significant. PBC yielded a larger plant compared to

PBS regardless of irrigation treatment. Skogholm cotoneaster grown in PBC also used less water to produce a gram of plant dry weight. Cotoneaster grown with On Demand irrigation grew the largest plant regardless of substrate but had a smaller root:top ratio than PM replacement. Plants irrigated On Demand had a greater amount of water applied later in the season, when the weather was hot and the plants were larger. The number of irrigation cycles per day for On Demand also increased throughout the study, and when evapotranspiration was at a maximum, was cycling between 5 to 7 times a day.

In the second study *Cotoneaster dammeri* 'Skogholm' was grown in PBS and irrigated with PM 0.2 LF, which again served as the industry control, and an On Demand treatment that irrigated to maintain CC initially between 94% and 98%. The upper and lower CC that served as irrigation triggers were adjusted downward over time to 92% to 96% and 90% to 94% to maintain a <.15 LF. Plant dry weight and root:top ratio were unaffected by the treatments. Total irrigation volume applied per container over the life of the study was not significantly affected by the treatments. As evapotranspiration increased throughout the season, On Demand increased mL of daily water application in mid-season (July), but by late season (August), both irrigation treatments were applying similar daily irrigation volumes. The number of irrigation cycles per day were remarkably similar early and midway in the study, whereas by late in the study, when evapotranspiration was at a maximum, On-Demand was cycling between 5 and 7 times a day. Data herein indicate the gravitational method of irrigation control is feasible in a nursery setting resulting in at least an equivalent sized plant with reduction in needed irrigation personnel for management decisions regarding irrigation volume and timing.

A Gravimetric Approach to Real-time Monitoring of Substrate Water Content in Container-grown Nursery Crops

by
Alison Elizabeth Prehn

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Horticultural Science

Raleigh, North Carolina

2008

APPROVED BY:

____
Dr. Aziz Amoozegar

____
Dr. Stuart L. Warren
Co-chair, Advisory Committee

____
Dr. Ted E. Bilderback
Co-chair, Advisory Committee

DEDICATION

I dedicate this work to my parents, my number one fans,

for guiding me in all my important life decisions

and supporting me in whatever I do.

And, most importantly,

for letting me call and complain on weekends.

BIOGRAPHY

Alison Prehn was born in Downers Grove, Illinois on November 10, 1980. She is the middle child in a family of three girls. Alison spent most of her childhood in the San Francisco Bay Area and considers herself a native of San Jose, California. Her mother and grandparents were always avid gardeners and Alison often helped her mom in the yard and played in her grandparents' gardens and woods outside of Madison, Wisconsin. This is probably where she gained her appreciation for horticulture, starting at an early age.

Alison attended Prospect High School in Saratoga, California and graduated in 1999, when she decided to attend the University of California at Davis. At UC Davis, Alison participated in intercollegiate track and field and rowing and took every possible general education class before she decided to major in Environmental Horticulture and Urban Forestry in the summer of 2002. She realized she never wanted to sit all day at a desk and knew horticulture would give her opportunities to be outside. She graduated in June of 2004 with a double specialization in floriculture/nursery production and urban forestry. Alison then worked for a landscaping and tree care company in the small town of Nevada City, California in the foothills of the Sierra Nevada Mountains. She later took a job at Pioneer Hi-Bred, International in Woodland, California as a research assistant in the maize pathology department. In 2006 she decided she missed academia, desired more horticultural knowledge, and wanted an adventure. She moved to Raleigh, North Carolina and began a master's program in Horticultural Science and surprised herself by not only earning a master's degree, but by becoming active in graduate extracurricular programs and also by teaching, which she never thought she'd possess the confidence to do. She will move to McMinnville, Oregon in the summer of 2008 to begin her nursery career as a production trainee at Monrovia Growers in Dayton, Oregon.

ACKNOWLEDGEMENTS

I am extremely grateful to have had such amazing advisors as Stu Warren and Ted Bilderback. I would like to thank Stu for tolerating my many visits to his office when he was extremely busy with other things and for always setting aside time to talk. I also would like to thank him for not abandoning me when he left for a job at Kansas State University, and for juggling my neediness with his new job as department head. And finally, for leaving a lot of things to me to figure out in order to learn to become more independent. I'd like to thank Ted for his practical knowledge and expertise which was invaluable throughout my experiment, and also for always providing an open door and time to chat, and for his persistence in getting me an answer, especially sitting down with me and figuring out equations when Stu was out of town.

Many, many thanks to Jim Owen, my "third advisor", because he was always there when everyone else was too busy! I couldn't have gotten through my program without him (at least not in two years!) and he was an invaluable resource. I appreciate that he was always there for edits and questions and emails and phone calls, even though he had no obligation to help and had to put up with me when I frequently did stupid things, like send him the old version of Chapter 1 to edit. Thank you to Aziz Amoozegar for soil science help and guidance.

I'd also like to thank William Reece, without whom I'd still be plugging away at SAS code. He also deserves thanks for all his time and effort installing my load cells and always making sure things were running smoothly. Thank you to Helen Kraus for helping with statistics crisis among other things. Thank you to Greg Kraus for putting in so many hours at the load cell pad and for tolerating my panicked emails, and without whom the load cell program would never have been successful. I would also like to acknowledge Beth Harden for helping with substrate physical property analysis.

I am extremely grateful to my research family. They're the best group of people I could have assembled. A special thanks to Michelle McGinnis, who passed down invaluable "inside" knowledge, Toni Pridemore, to whom I could entrust my entire experiment while I was on vacation, John Wooldridge, Adam Lowder, Clayton Long, and Kristen Walton. I would not have been half as efficient without them and our East Village excursions. Thank you also to Ryan Pekarek, who never tired of my questions, and my fellow graduate students who provided constant laughs in the grad office. You'll be missed. And especially thanks to Kirby "the killer kitty", who provided comic relief and snuggling sessions when I needed them most.

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INTRODUCTION AND LITERATURE REVIEW

Due to continuing urbanization and the occasional drought water restrictions are becoming more prevalent throughout the horticultural world. In addition, the Environmental Protection Agency (EPA) has started enforcing the laws in the Federal Clean Water Act and many states have created water quality laws to force agriculture to comply (Lea-Cox and Ross, 2001; Sharma et al., 2008; EPA, 2008). The green industry needs to be more stringent than ever before about finding ways to minimize run-off and water use (Lea-Cox and Ross, 2001). Thus, efficient water management should be the core of container-grown crop production.

Best Management Practices (BMPs) have been created to provide growers guidelines and strategies to minimize or more effectively use vital resources. BMPs include using controlled release fertilizers (CRFs), building retention ponds to recycle irrigation water, using substrate with a high-water holding capacity, and implementing practices that result in zero to little run-off such as cyclic irrigation and reduced leaching fraction (LF = water leached ÷ water applied) (Chen et al., 2001; Fain et al., 2000; Sharma et al., 2008; Yeager et al., 2007).

In order to implement successful water conservation strategies, growers need to know how much available water is in the substrate at any given time. One way to determine this is to track container capacity. Container capacity is the maximum amount of water held in the substrate after all free water has drained (Handreck and Black, 2002; Yeager et al., 2007). BMPs suggest that moisture levels in containers can be determined by color or feel of stubstrate, indicator plants, evaporation pans, moisture probes, or by container weight

(Yeager et al., 2007). Indicator plants can be used by monitoring one plant from a crop they may tend to dry out before the others, and watching it for drought stress symptoms such as drooping leaves or color changes. Evaporation pans measure evaporation losses via evaporation pans and water is added in quantities recommended by water use curves for a particular crop (Reed, 1996). Tensiometers measure moisture levels in containers by measuring the tension of a water column in the instrument when water is taken up through a porous ceramic cup. Tensiometers can be unreliable because they depend on a continuous water column that is often broken when the substrate is dried out (Haman and Yeager, 2007; Handreck and Black, 2002). Several electrical probe moisture sensors are available commercially. Nemali and van Irsael (2006) designed an irrigation monitoring system using time domain reflectometry (TDR) moisture sensors (ECH$_2$O-10 probes, Decagon, Pullman, WA, USA). These sensors are used to measure volumetric water content measurements which are monitored by a datalogger which turns irrigation on as needed. However, this method relies on probe contact with the substrate, which with soilless substrates can be difficult, given the course nature of particles. In addition, probe calibration is different for different substrates and oftentimes substrate physical properties change over time due to decomposition, causing further recalibration. Furthermore, the accuracy of probes and tensiometers depend on their position in the container—the higher up they are, the drier the substrate, and the higher the potential for over-watering, and vice versa if the device is moved lower in the container (Jim Owen, phD, extension specialist and assistant professor, Oregon State University, personal commun.).

We believe the best way to monitor substrate water is via weight. Weight measurement of substrate water is simple and direct—water loss equals weight loss. This method has been employed in many different ways. Ekanayake et al. (1993) calculated daily evapotranspiration losses in rice (*Oryza sativa*) by weighing containers daily to determine weight loss and replacing all water lost. Ray and Sinclair (1998) weighed maize (*Zea mays*) and soybeans (*Glycine max*) in containers in a drought stress experiment. They saturated and drained the containers overnight before obtaining an initial weight for each system. They then weighed the containers each afternoon at a set time and daily evapotranspiration was calculated as the difference in the initial container weight minus current container weight. A concern with using gravimetric techniques to control irrigation is that water will not fully penetrate the substrate, because often small amounts are added at frequent intervals. However, Earl (2003), found that was not the case. He used a null-balance lysimeter connected to a computer system to automatically add water to containers once they lost a certain amount of water. He concluded that this technique was useful in greenhouse conditions because the soil water and root distribution were uniform throughout the system. These conditions would also be similar to a nursery environment suggesting that container weight may be a valuable tool in determining available water in the container.

Leaching Fraction

BMPs for the southeastern United States indicate that the quantity of water to apply should be based on the amount of water lost since the last irrigation event (Yeager et al., 2007). Current recommendations are a 0.1 to 0.2 leaching fraction or 90% to 80% application efficiency, respectively, to ensure proper rewetting of the substrate, with LF not to exceed 0.25. Unfortunately, for many growers how much water to apply (volume) and when to apply it (timing) are based on work hours and irrigation system limitations (pump run time). For most growers it is difficult to determine the available water in the substrate throughout the day. Thus, growers often apply 50% to 150% more water than is necessary to ensure the substrate is re-hydrated (Ted Bilderback, Ph.D, nursery specialist and professor, North Carolina State University, personal commun.). In addition to water lost, this overage of water application can be measured monetarily as labor access to irrigation zones, pump run time, disease management, and irrigation system requirements.

Poole and Conover (1982) conducted one of the earliest experiments which examined 0.10 LF versus no LF in combination with various rates of controlled release fertilizer in a greenhouse. They reported that no LF in combination with the recommended rate of fertilization (no over-application) maximized water efficiency and water use efficiency of productivity (WUE_p = mL water retained in substrate ÷ plant mass). As an added bonus, this minimized polluting leachates. Little research, however, has examined how plants respond to low LFs in a nursery production environment. Results from Groves et al. (1998) and Tyler et al. (1996b) suggested with CRFs at typical rates combined with low LF, plant growth was not affected. These studies were conducted on an outdoor gravel surface so some leaching occurred with rainfall. Thus it would appear that with careful water management a near zero LF should be feasible without sacrificing crop growth.

Water Stress

Zero LF does not imply simply reducing irrigation volume. Too little water can lead to plant stress which can be detrimental. If low volumes of water are applied to eliminate leaching without regard to maintaining adequate water in the container then reduction in growth will occur. Schuch et al. (1995) applied set volumes of water (240 $mL\cdot d^{-1}$ or 120 $mL\cdot d^{-1}$) to six cultivars of poinsettias growing in a peat-based substrate. The low irrigation volume reduced all growth parameters in all cultivars by 36% to 41%. Even with no LF, the substrate must be returned close to CC or reductions in growth will occur.

Plants grown with inadequate water will have reduced growth rates resulting from decreased photosynthetic activity (Taiz and Zeiger, 2003). Abscisic acid is produced in response to a dry root environment and transported to the guard cells (Davies et al., 1994). This, in turn, signals Ca^{+} to flow into the cells, which opens anion efflux channels. The membrane is depolarized and K^{+} efflux channels are then activated and K^{+} flows out, which causes water to flow out of the guard cells and the stomata to close. Closed stomata result in decreased photosynthesis, which decreases the plant's ability to use all its resources (sunlight) and maximal growth is not obtained (John Williamson, phD, professor, North Carolina State University, personal commun.). Furthermore, if exposed to drought conditions for too long, plants can enact "stress memory", which allows them to use fewer resources in preparation for possible future similar stressful conditions. This also reduces plant growth (Goh et al., 2003).

Drought also impacts substrate properties. Pine bark becomes hydrophobic when it is allowed to dry out below 40% moisture content (Reed, 1996). If the substrate is hydrophobic, water will channel through the substrate quickly instead of being retained in the micropores. It takes large quantities of water to re-hydrate the substrate. Potentially much water can be wasted trying to re-hydrate the pine bark that may as well have been used to irrigate the plant to prevent such drying in the first place.

Soilless Substrates

Physical properties are important components of all substrates and usually include: air space, porosity, container capacity, available water, unavailable water, and bulk density (Bilderback et al., 2005).

Substrates other than soil are used in container production because they are readily and cheaply available in the local market and growers can also vary the physical properties of substrates depending on their individual needs. In the southeastern United States a pine bark and sand mixture is a common substrate used in container production. Sand is added to substrates to improve physical properties and increase bulk density which stabilizes pots and prevents blow-over (Reed, 1996).

One way to increase available water in the container (and to avoid hydrophobic conditions) is to use a substrate with a high water-holding capacity. Substrates with a large proportion of smaller particles hold more water (Yeager et al., 2007) as do substrates containing particles with intra-pores, like calcined clay (Spomer, 1998). Calcined clay is a good choice for amending container substrates as it increases drainage and air space (Reed, 1996). Owen (2006) found that 'Skogholm' cotoneaster grown in an 8 pine bark : 1 clay (by vol.) mixture used up to 24% less water than when grown in a 8 pine bark : 1 sand. He also reported that clay, when used in place of sand, reduced daily irrigation applied by 18% and that water use efficiency [WUE_p = (total volume water applied - volume leached) ÷ total dry mass of the plant] increased by 15%.

Cyclic Irrigation and Timing

Time of irrigation application also affects water use and efficiency. Water use efficiency of productivity determines how many milliliters of water are required to produce one gram of dry mass. Several studies have demonstrated that irrigating during peak evapotranspiration (PM) increased plant growth compared to early morning irrigation (Ruter, 1998; Warren and Bilderback, 2002). This research was conducted with spray stakes which lose very little water to evaporation because the water is applied directly to the substrate. However, pre-dawn irrigation is still the recommended practice for overhead irrigation because losses to evaporation are at minimum at this time.

Cyclic irrigation is defined as applying several applications of water throughout the day rather than applying all the water in a single irrigation event (Beeson and Haydu, 1995). When water is applied to a container substrate a wetting front is formed immediately in the substrate 7.6 to 10 cm in depth. Water first enters macropores, and given time, micropores. Container capacity is defined as the amount of water held in a substrate immediately after drainage, or when the micropores are filled with water and the macropores are filled with air (Handreck and Black, 2002). If water is applied in several small amounts over a day, this front is given time to spread out laterally and seep into all pores throughout the wetted area. When the second cycle of irrigation in a cyclic application is applied, this front is extended down and again if given time will move laterally and fill in all available pore spaces. Repeating this process results in a more uniformly wet substrate as well as minimal leaching (Bilderback, 2007). This is the process that makes cyclic irrigation so successful in increasing water application efficiency, or irrigation efficiency [WAE = 100 × (volume water applied to container – volume leached) ÷ (volume of water applied to container)] (Warren and Bilderback, 2005).

Fare et al. (1994) observed that effluent volume was 34% less when 13 mm of water was applied over three cycles compared to 39 mm of water applied with one application. Lamack and Niemiera (1993) obtained a high WAE (86%) when 600 mL of irrigation was applied in 50 mL applications with at least 40 min between applications, compared to a WAE of 62% when 600 mm was applied in a single application.

Along with cyclic irrigation, another important component of nursery irrigation is substrate wetness, or substrate water deficiency. While it makes sense intuitively that WAE would increase as substrate moisture deficit increased, Tyler et al., (1996) found when substrate was allowed to dry out to 79% CC, macropore channeling occurred dramatically decreasing WAE. This is due to the hydrophobic nature of pine bark--if it becomes too dry then moisture retention decreases (Beeson and Haydu, 1995).

Initially there was concern as to whether cyclic irrigation could adequately wet the substrate all the way through to the bottom of the container. Zur (1976) used time averaged application rate [TAAR = water applied daily (mL) ÷ total application time (min)] to show that cyclic irrigation can be used effectively to control the wetting depth of the soil profile. In other words, the duration of time irrigation is applied is directly determined by the amount of time between irrigation events. Lower TAAR usually increased water application efficiency.

At NC State University we conducted two studies which used load cells to weigh containers to determine when to irrigate and how much water to apply to grow the maximum-sized plant possible with minimum leaching. The results from these studies are presented in the following chapters.

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Chapter 1

A gravimetric approach to real-time monitoring of substrate water content in container-grown nursery crops in sand and clay amended substrates.

(In the format appropriate for submission to HortScience)

Alison E. Prehn[1]

[1]Graduate Research Assistant, Department of Horticultural Science, North Carolina State University, Raleigh, NC 27695

ABSTRACT

Water management should be the core of container nursery production as it is linked directly to both water and nutrient use efficiency and ultimately environmental impact. In this study the gravimetric technique was used via a load cell/computer interface to schedule irrigation—to determine irrigation volume and time of water application. The goal was to determine the feasibility of an irrigation system that relies on real-time monitoring of substrate weight. *Cotoneaster dammeri* 'Skoghom' was grown in 14-L containers in either a sand (PBS) or clay (PBC) amended (11% by vol.) pine bark based soilless substrate. Two treatments were added to represent common industry standards (controls): a PBS substrate irrigated at 0100, 0400, 0700 HR (AM 0.2 LF) or at 1200, 1500, and 1800 HR (PM 0.2 LF) to maintain a targeted 0.2 LF. The remaining treatments were either PBS and PBC, each of which were irrigated at either 1200, 1500, and 1800 HR, adding as much volume as needed to raise the container capacity (CC = total volume retained in substrate after just drained) to 98% (PM Replacement) or anytime throughout the day up to 98% container capacity whenever CC dropped below 94% (On Demand) regardless of time. Top, root, and total dry weight were significantly different between substrates with PBC yielding a larger plant in all cases. PBC also used less water than PBS to produce a gram of dry weight. Crops irrigated On Demand were the largest but had a smaller root:top ratio than PM Replacement. PM 0.2 LF grew a larger plant with a comparable amount of water compared to AM 0.2 LF. Data herein indicated the gravitational method of irrigation is feasible in a nursery setting and can result in a larger plant than traditional methods, reduction in needed irrigation personnel for management, and maintenance of <0.3 LF.

INTRODUCTION

Irrigation of container-grown nursery crops is oftentimes inefficient, creating wasteful use of water and discharging potential pollutants via leaching or runoff. Rapid population growth, particularly in the southeastern United States, has recently increased awareness surrounding water availability and resource conservation. A growing public and industry environmental consciousness has emerged. This has lead to national, regional, and local regulations being enacted to ensure that water quality is unaffected by nursery practices (NC Division of Water Quality 2008), and that excess water is not used. Thus, it has become increasingly important for growers to be able to irrigate more efficiently by increasing both water application and water use efficiency. This in turn reduces the leachate/runoff that can degrade water quality both on and offsite. Appropriate research has ensued to provide growers the needed tools to increase production efficiency and environmental stewardship.

Owen et al. (2008) reported that pine bark substrates amended with mineral aggregates (clay) increased container capacity (CC) and available water (AW) 5% and 4% by volume, respectively, which resulted in a 17% increase in water use efficiency of productivity {WUE_p = total irrigation volume retained in substrate for the season (mL) ÷ total plant dry weight (g) [mL of water required to produce 1 g of plant dry mass]} compared to sand-amended pine bark. Beeson and Haydu (1995), Tyler et al. (1996), Ruter (1998) and others demonstrated cyclic application of irrigation increased water application efficiency {WAE = 100 × [volume retained in substrate (mL) ÷ influent volume (mL)]} and decreased leachate volume through slower, efficient substrate rehydration. In addition, Warren and Bilderback (2002) demonstrated irrigating in the afternoon hours (1200, 1500, and 1800 HR) was beneficial by minimizing plant water stress and substrate temperature. Current leaching fraction (LF = effluent volume ÷ influent volume) recommendations are 0.1 to 0.2 LF, i.e. 90% to 80% application efficiency, respectively) to ensure proper rewetting of the substrate with LF not to exceed 0.25 (Yeager et al., 2007).

The gravimetric technique (using weight in some manner) for irrigating plants has been used by some researchers to determine water content in a container and to detect points at which plant water stress may occur (Ray and Sinclair, 1998). Lysimeters have long been used in field irrigation of agronomic crops to measure rate of evapotranspiration (Miller and Gardiner, 2001). Earl (2003) used a computer-automated null-balance lysimeter to accurately determine drought-stress in greenhouse experiments. Beeson (2007) successfully used a suspension lysimeter in a nursery setting to measure AW in a container. However, little work has been done using a gravimetric method in a container nursery to control irrigation scheduling. Irrigation scheduling includes determining both irrigation volume and timing of water application. Thus, the objective of this study was to determine the feasibility of using weight as a means to control irrigation timing and volume for containerized woody and perennial crop production.

MATERIALS AND METHODS

The experiment was a 2 x 2 factorial in a randomized complete block design with four blocks and four containers per replication. The main factors were a pine bark substrate amended with a mineral aggregate [0.25 to 0.85 mm calcined, low volatile material (LVM) palygorksite-bentonite from Ochlocknee, GA (Oil-Dri Corporation of America, Chicago, IL)

(Moll and Goss, 1997)] at 11% (by vol) (hereafter referred to as PBC) or coarse, washed builder's sand at 11% (by vol.) (hereafter referred to as PBS) and two irrigation parameters which included irrigating to return the substrate to 98% CC as determined by weight at 1200, 1500, and 1800 HR (hereafter referred to PM Replacement), and irrigating to return the substrate to 98% CC when it reached 92% CC as determined by weight regardless of time (hereafter referred to as On Demand). In addition, two treatments were added to represent common industry standards (controls): a PBS substrate irrigated at 0100, 0400, 0700 HR or at 1200, 1500, and 1800 HR to maintain a targeted 0.2 LF (hereafter referred to as AM 0.2 LF and PM 0.2 LF, respectively). All substrates were amended with dolomitic limestone [$CaMg(CO_3)_2$] and a micronutrient fertilizer (Micromax, Scotts Company, Marysville, OH) at a rate of 1.8 kg m^{-3}. There were a total of six treatments: (1) PBC PM Replacement, (2) PBS PM Replacement, (3) PBC On Demand, (4) PBS On Demand, (5) AM 0.2 LF, and (6) PM 0.2 LF.

Real time monitoring of container weight (plant + substrate + container) was performed using a low profile, two-beam single aluminum (Al) point load cell with a 30 kg capacity (± 0.02% error) (Model RL 1042, Tedea-Huntleigh Inc, Covina, CA). The load cell was mounted between two Al plates [15 cm x 15 cm, 0.06 cm thick]. One 0.6 cm Al spacer was attached between the top and bottom plates and the load cell to keep debris from interfering with load cell movement. The top surface area was expanded with a 23 cm x 23 cm square, 3 mm thick Al plate. An Al foil skirt was constructed to fit around the bottom of the entire system to keep debris from impeding load cell movement. The load cells were connected to a CR23X micrologger® via an AM32 multiplexer (Campbell Scientific, Logan, Utah). Weight was recorded every 15 min, and every 10 sec when the crop was being irrigated. Within each treatment and block, one plant was positioned on a load cell (total of 24).

Container capacity was determined by saturating containers at ~20 d intervals. Saturation was achieved by placing each container from the load cell into a 20 L bucket which was filled with water at ~1800 HR. When the substrate was fully saturated (~2 hr) (as evidenced by a glossy sheen of water at the substrate surface), the containers were returned to the load cells and allowed to drain until 0400 HR the following morning. At 0400 HR the computer recorded weights for each of the 24 containers, and this was deemed CC.

This study was conducted on a gravel pad at the Horticulture Field Lab (lat. 35°47'37'N, long. -78°41'59'W) at North Carolina State University, Raleigh. Uniform, rooted stem cuttings of *Cotoneaster dammeri* C.K. Schneid. 'Skogholm' were potted into black 14-L containers (C-2000, Nursery Supplies Inc., Chambersburg, Penn.) on 11 May 2006. Containers were top-dressed on 13 May 2006 with 54 g 19.0N-1.8P-6.4K (19-4-8 six month controlled-release fertilizer, Harrell's, Lakeland, FL). All plants received daily irrigation with a targeted LF of 0.2 until the experiment was initiated on 5 June 2006.

Influent and effluent from each treatment were measured weekly from irrigation water applied via pressure-compensated spray stakes [Acu-Spray Stick; Wade Mfg. Co., Fresno, Calif. (200 $mL \cdot min^{-1}$)]. These data were used to determine water volume, water use, LF, time averaged application rate [TAAR = daily influent volume (mL) ÷ application duration time (min)], and WAE as affected by each treatment. WUE_P was also calculated. These data were also used to adjust irrigation volume to maintain 0.2 LF for the controls

(AM 0.2 LF and PM 0.2 LF). Electrical conductivity (EC) and pH of the substrate solution were measured every 2 weeks throughout the experiment via the pour-through extraction procedure (Wright, 1986).

Net photosynthesis (P_n) and stomatal conductance (g_s) were measured on 4 Sept. 2006 [92 days after treatment initiation (DAI)]. One plant from each of the PBS replications (controls and irrigation treatments) was measured in the AM (1030 to 1130 HR) and PM (1530 to 1630 HR). The measurements were taken using a LI-6400 open, portable gas exchange system with a LI-6400-05 conifer chamber (LI-COR, Lincoln, Neb.). Measurements were conducted on the intact terminal 5 cm of stem with approximately 5 fully expanded leaves (8.3 cm^2 ± 0.57 SE) under natural light in which photosynthetic active radiation remained >1600 $\mu mol^{-2}s^{-1}$. Carbon dioxide in the chamber was 400.4 $\mu mol \cdot mol^{-1}$ ± 0.2 SE in the AM and 374.3 $\mu mol\ mol^{-1}$ ± 13.7 SE in the PM. Vapor pressure deficit in the AM and PM was 2.39 kPa ± 0.07 and 1.84 kPa ± 0.04, respectively. Water use efficiency of photosynthesis (WUE_{pn}) was calculated as $P_n \div g_s$.

Ten cylindrical aluminum cores, five 347.5 cm^3 and five 100 cm^3, were buried in six fallow containers of each substrate and placed under overhead irrigation at the same location as the research study. After 9 weeks, the 347.5 cm^3 cores were extracted and total porosity (TP), CC, AW, and air filled porosity (AS) were determined using the NCSU Porometer™ as described by Fonteno and Bilderback (1993). Unavailable water (UW), water held in the substrate at ≥1.5 MPa, was determined with the 100 cm^3 cores via a procedure developed by Milks et al. (1989). Bulk density (D_b) was determined using oven dried 110°C (230°F) substrate in 347.5 cm^3 volume cores. Particle size distribution of approximately 500 cm^3

oven dried substrate 110°C (230°F) was determined gravimetrically using 6.30, 2.00, 0.71, 0.50, 0.25, and 0.106 mm soil sieves. Particles ≤0.106 mm were collected in a pan. Sieves and pan were shaken for 5 minutes with a RX-29/30 Ro-Tap® test sieve shaker (278 oscillations $minute^{-1}$, 150 taps $minute^{-1}$) (W.S. Tyler, Mentor, OH).

At 104 DAI, tops (aerial tissue) were removed from three plants from each plot/replication (total of 12 plants/treatment). Roots were placed over a screen and washed with a high pressure water stream to remove substrate. Tops and roots were dried at 65°C until a stable weight was reached and then weighed. Root:top ratio [(RTR) = root dry weight ÷ top dry weight] was calculated. All data from the 2 x 2 study were subjected to analysis of variance (ANOVA) with means separated via Fisher's Protected Least Significant Difference (LSD), $P = 0.05$. Treatment comparisons to the controls were made by single degree of freedom linear contrast tests.

RESULTS AND DISCUSSION

Substrate Physical Properties. There were no differences in TP, CC, AS, or AW between the sand and clay substrates. Bulk density and UW were significantly different between the two substrates, with Db of PBC significantly less and UW of PBC significantly more than PBS (Table 1). For this reason, sand is often added to pine bark to increase bulk density and make containers heavier and more resistant to blow-over. These results are contradictory to Warren and Bilderback's (1992) findings that clay-amended pine bark changed pore size distribution which increased AW and decreased AS. However, we still believe that clay has a greater water-holding capacity than sand due to our plant response findings.

Plant response. The irrigation x substrate interaction was non-significant for all parameters (Table 2); therefore, only the main effects of irrigation and substrate are presented. Skogholm cotoneaster grown in PBC had significantly larger top (39%), root (25%), and subsequently total plant dry weight (37%) compared to plants grown in PBS (Table 3). This is similar to data reported by Owen et al. (2008). In contrast, RTR was unaffected by substrate. Thus, all plants maintained similar carbon allocation between tops and roots even though plants grown in PBC were significantly larger. Water use efficiency of productivity increased by 36% (used 154 fewer mLs of water to produce a g of dry mass) when plants were grown in PBC compared to plants grown in PBS. These data support the results of Owen et. al. (2008), i.e., cotoneaster grown in a clay-amended pine bark has improved WUE_p. In contrast, plant dry weight and WUE_p were unaffected by irrigation treatments (PM Replacement and On Demand) whereas RTR was greater when grown with PM Replacement compared to On Demand irrigation. This likely has to do with when plants allocate carbon to the root system, which will be discussed later.

Within the controls, when plants were irrigated between 1200 and 1800 HR (PM 0.2 LF), top dry weight was on average 60% larger than when irrigated cyclically pre-dawn (AM 0.2 LF) (Table 3). This is similar to reports by Warren and Bilderback (2002), Keever and Cobb (1985) and Beeson (1992). Not surprisingly, PM cyclic irrigation is becoming increasingly popular among growers due to increased plant growth (Ted Bilderback phD, extension specialist and professor, North Carolina State University, personal commun.). However, using a load cell (On Demand or PM Replacement) to control irrigation scheduling produced additional top dry weight (50% and 44%, respectively) of ‘Skogholm’ cotoneaster compared to the PM industry control (PM 0.2 LF). Thus, 'On Demand' irrigation could shorten the production time to grow a marketable-sized 15 L 'Skogholm' cotoneaster crop with an accompanying reduction in water usage. Both irrigation treatments that were applied in the PM (1200 to 1800 HR) (PM Replacement and PM 0.2 LF) produced equivalent plant growth. However, minimum labor was required when irrigation volume was determined by weight loss (PM Replacement) compared to determining LF on a weekly basis (PM 0.2 LF) (personal experience).

The RTR for the AM 0.2 LF treatment was significantly greater than plants grown with PM replacement and On Demand. Plants under drought stress tend to produce a larger RTR as more carbon is allocated to the root system (Taiz and Zeiger, 2002). Therefore, plants grown with On Demand irrigation scheduling appeared to be under less stress, more likely a stress memory from inadequate rehydration throughout the day creating a baseline for physiological processes in which water would not become limiting (Goh et al., 2003). A small RTR has caused some concern among plant consumers based on the assumption that a plant with a smaller root system in relation to the size of the top might experience greater transplant shock. However, Cabrera and Devereaux (1999) reported RTR had no effect on survival or growth after transplanting into the landscape.

Water Use. Even though WUE_p increased when Skogholm cotoneaster was grown in PBC, the total volume of water applied via irrigation was greater for cotoneaster in PBC compared to PBS (Table 4). However, irrigation volume was unaffected by irrigation schedule (PM replacement, On Demand). Total volume applied was significantly less for both 0.2 LF treatments compared to the load cell-controlled irrigation treatments which is likely why dry weight was less in the 0.2 LF treatments.

Leaching fraction for the AM and PM industry controls were 0.34 ± 0.04 and 0.15 ± 0.05, respectively (Table 4). Both of these LFs are adequate to maximize growth. AM 0.2 LF was greater because there wasn't much evapotransporation taking place in the pre-dawn hours, so more water came out the bottom. On Demand irrigation, regardless of substrate, had LF's close to the ideal 0.2 LF. The LF for PM Replacement was above the recommended maximum of 0.25 (Yeager et al., 2007). For both On Demand and PM Replacement, these LF values were achieved without the usual labor required to manually measure and adjust LF. We suspect the LF of the gravimetric-based treatments could be decreased by reducing the low and high percent CC irrigation targets.

An unplanned for phenomenon occurred at > 45 DAI--excessive amounts of effluent were observed, particularly in the PM Replacement treatment. As stated previously, weight at 100% CC was determined when saturating the container from the bottom which allowed true saturation of micro and macro pores (Handreck and Black, 2002). However, when water was applied to the substrate surface, the macropores saturated before the micropores. This resulted in water leaching out the bottom of the container before having infiltrated all micropores and prevented the container from reaching 100% CC, or even 98% CC. Micropores are difficult to refill with water from micro-irrigation or non-saturating irrigation events (Hillel, 1998). This hysteretic effect results in a reduction in the maximum CC that the system is able to reach over time (Jim Owen Ph.D, nursedry specialist, Oregon State University, personal communication). Micropores previously filled during saturation were unable to be refilled making 98% CC difficult to achieve. As a result excess water was applied until surface-pooling occurred simultaneously with drainage, finally allowing the target weight (98% CC) to be achieved. This likely happened as plant growth increased which increased water loss via evapotranspiration from the micropores which could not then be refilled. Reaching 98% CC became more difficult as there was inadequate energy for water to move from macropore to micropore, and channeling occurred. This may be why the overall LF for PM Replacement was elevated. From these observations we concluded that 98% CC is an unrealistic percentage, and that 98% or 100% CC can only be reached after a rain event as observed by Owen, et al. (2006). Future research should examine the possibility of reducing the upper percent CC shut-off point.

Figures are shown for water use and evapotranspiration on 8 August 2006. High temperature for that day was 38.9°C, there was no precipitation, average photosynthetically active radiation was 420.2 μmol·s m^2, relative humidity 65%, and wind speed was 6.3 kph. AM 0.2 LF began the day (0000) at about 87% CC, where it ended the day before (data not presented) (Fig. 1A). For the first irrigation event that day WAE was 82% and accounted for 36% of the total water gain for the day. The second irrigation event a WAE of 80% and added 35% of the total irrigation, and the third event had a WAE of 69% and added 30% of the water for the day, returning the container to about 95% CC before sunrise. Shortly after sunrise (~0800 HR) evapotranspiration began, and CC decreased throughout the rest of the day, reaching an average CC of 86% by late afternoon.

These data illustrate that the first irrigation application in the AM hours is most efficient, resulting in the most water obtained by the substrate. The closer the system was to

100% CC, the higher the decrease in WAE. This follows research by Owen (2006), Beeson (1992), and Tyler et al. (1996), who found that the first irrigation event always had the highest WAE. In effect, a grower may decide to apply more water during the first cycle. This would be an advisable practice as long as the substrate is not allowed to become hydrophobic before water application begins as this would increase channeling and efficiency would greatly decrease. Lamack and Niemiera (1993) found a "water-holding threshold" beyond which pine bark can no longer absorb water as fast as it is applied, resulting in decreased water retention.

There were smaller differences in WAE between the three cycles of the PM 0.2 LF irrigation treatments. The first irrigation event had a WAE and total weight gain for the day of 77% and 35%, respectively, 74% and 33% for the second cycle, and 67% and 32% for the third cycle. When evapotranspiration began after sun-up, container weight decreased until irrigation occurred at 1200, 1500 and 1800 HR. Container capacity never dropped below ~90% in the PM 0.2 LF treatment which may explain the differences in plant growth between PM 0.2 LF and AM 0.2 LF.

The PM Replacement treatments tended to lose much more water between irrigation events, possibly due to the larger plant size. The PBS PM Replacement treatment had a 87%, 85%, and 37% WAE for each irrigation application, respectively, and total water applied was 42%, 41%, and 18% of the total water for the day. In contrast, the PBS On Demand treatment had relatively stable WAE values throughout the day, likely the substrate was kept moist throughout the experiment. There were a total of five cycles on 8 August and the

WAE's were 98%, 92%, 94%, 91%, and 92%. As with the other treatments, the first irrigation event was the most efficient.

Figure 1A shows similar results for PBC PM Replacement and On Demand. The weight for the PM Replacement treatment in the time between irrigations was lower than for PBS. This is because the plants grown in PBC were bigger and therefore used more water. This demonstrates that the gravitational system can work for any substrate and does not need to be calibrated for different substrates.

The On Demand irrigation schedule was able to keep LF low and water use efficiency high. The substrate in this treatment never reached < 92% CC. The On Demand irrigation treatments for both substrates typically interrupted the rapid evapotranspiration and decrease in weight of the container which occurred after sun-up and before 1200 HR. The PM irrigation treatments were programmed to irrigate between 1200 and 1800 HR. In contrast, the On Demand treatments started, on average, in the late morning (1026 HR) with the last irrigation event, on average, at 1400 HR (Table 5). In the month of August the On Demand treatment was irrigated as many as 10 times during the hottest part of the summer, maintaining CC above the lower set-point of 92%. This illustrates how much effort would be required for a grower to maintain a high percent CC without some level of automated control.

In early season, when evapotranspiration was the lowest, On Demand applied a daily average of 772 mL per container for each substrate whereas PM 0.2 LF required 1079 mL per container, a difference of 40%. This demonstrates the power of weight based application in contrast to a fixed LF. As the plants grew and temperature increased which increased evapotranspiration, On Demand increased to an average daily application of 1546 mL in July and an additional increase to 3187 mL by September. PM 0.2 LF increased to 1057 mL in July with an additional increase to 1237 mL by September.

The number of cycles for each treatment per day were remarkably similar early and midway in the study. However, by late in the study On Demand was cycling 5 to 7 times a day. The number of cycles apparently increased throughout the study as the first irrigation event for On Demand initiated earlier and earlier as evapotranspiration increased. Early in the study the first irrigation event began at 1100 HR for On Demand. Midway in the study the first irrigation event for On Demand occurred on average at 1000 HR and by August at 0900 HR vs. the fixed 1200 HR for PM 0.2 LF. In contrast, the last irrigation event for On Demand and PM 0.2 LF was similar over the entire study.

The TAAR varied throughout the study (Table 5). Lamack and Niemiera (1993) reported lowering the TAAR typically decreased leaching and increased WAE. We found that during the first month of the study TAAR was significantly lower for PM Replacement than the controls, whereas TAAR produced by On Demand was not different from the controls. However, from July to the end of the study the controls have significantly lower TAAR than the other treatments. All of the TAARs were less than 10 $mL \cdot min^{-1}$ which has been suggested as the irrigation target to maximize WAE (Warren and Bilderback, 2003).

For the duration of the study, none of the plants in any of the treatments reached < 70% CC (data not presented). According to Owen (2006), AW (water extracted ≤ 1500 kPa) would have been depleted at 60% CC, so in this study, none of the treatments exhausted AW. However, this is not reflected in the dry weights as plant weights varied significantly with treatment.

Substrate pH and electrical conductivity measurements. There were no irrigation x substrate interactions for any sample times for either pH or EC (data not presented). Substrate pH did not change drastically over the course of the experiment for any of the treatments, however, PBC was significantly greater than PBS at all samples times (Table 6). Even though there were significant differences in pH at three out of the seven samples times for irrigation treatments, the differences were small and probably not biologically important. There were no differences between the two controls and the controls were seldom different from the substrate and irrigation treatments.

Differences in EC occurred between the substrates at 56 and 67 DAI (Table 7). The PM Replacement and On Demand were significantly different at 12 and 25 DAI, when On Demand was lower, probably because this treatment was being irrigated very little when the plants were still small. At 56 DAI On-Demand had a greater EC, and PM 0.2 LF had a significantly greater EC at day 37, which do not appear meaningful. Electrical conductivity spiked during the second week of the experiment for all treatments, but this was likely due to the increasingly warmer weather and a resulting flush of nutrient release from the CRF. Levels of EC in PM 0.2 LF were significantly greater than the other irrigation treatments at 12, 37 and 67 DAI possibly due to the reduced LF. The decreased EC levels did not negatively affect growth as both PM Replacement and On Demand had greater total dry weight compared to PM 0.2 LF.

Photosynthesis and stomatal conductance. Even though there were dramatic differences in growth between the treatments, Pn, g_s and WUE_{Pn} were affected by neither irrigation treatments nor controls. According to van Iersel (2003), leaf gas exchange measurements similar to that used here often do not correlate well with total plant growth or yield.

An 8:1 pine bark:clay substrate mixture can grow a larger plant using less water than an 8:1 pine bark:sand mixture, supporting previous research reported by Owen (2006). Using a load cell/computer interface as a gravimetric means for irrigating on demand or replacing all water lost at 1200, 1500, and 1800 HR results in a larger plant than traditional methods but with comparable WUE_p. Leaching fractions were not remarkably different with the load cell system. By adjusting the percent CC at which the system shuts on and off growers should able to maximize growth with reduced LF as well as generate an extremely favorable WUE.

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Table 1. Substrate particle size distribution of pine bark amended substrates ~105 days after potting.

Substrate[z]	Bulk Density	% Total porosity[y]	% Container capacity[x]	% Air space[w]	Unavailable water[v]	Available water[u]
	g cm^{-3}	Percent volume				
PBS	0.43 a[t]	73.3 a	49.3 a	24.0 a	27.2 b	22.1 a
PBC	0.37 b	71.6 a	48.5 a	23.0 a	27.8 a	20.7 a

[z]PBS = 8 pine bark : 1 sand with 1.8 kg·m^{-3} dolomitic limestone (v/v); PBC = 8: 1 pine bark : 1 clay with 1.8 kg·m^{-3} dolomitic limestone (v/v).

[y]Based upon percent volume air and water of a 7.6 × 7.6 cm core at 0 kPa.

[x]Measured as percent volume water of a 7.6 × 7.6 cm core at 0 kPa.

[w]Measured as percent volume air of a 7.6 × 7.6 cm core at 0 kPa.

[v]Based upon percent volume water retained of a 7.6 x 7.6 cm core at 1500 kPa.

[u]Available water = container capacity – unavailable water.

[t]Any means within a row (treatment not followed by the same letter are significantly different as determined by Fishers LSD $P = 0.05$

Table 2. P-values showing irrigation, substrate, and the irrigation x substrate interaction on plant dry weight (g), root:top ratio, and water use efficiency of productivity[z].

Treatments	Top dry weight	Root dry weight	Total dry weight	Root:top ratio[y]	WUE_p
	g				mL g^{-1}
Irrigation	0.234[x]	0.459	0.333	0.027	0.472
Substrate	0.001	0.033	0.002	0.148	0.002
Irrigation x substrate	0.379	0.940	0.427	0.661	0.214

[z]WUE_p = volume of water retained by substrate (mL) ÷ total plant dry weight (g).

[y]Root:top ratio = root dry weight ÷ top dry weight.

[x]*P* values.

Table 3. Effect of substrate, irrigation treatment, and industry controls on plant dry weight (g), carbon allocation, and water use efficiency of productivity.

Main Effects	Top dry weight	Root dry weight	Total dry weight	Root:top ratio[z]	WUE_p[y]
	g				$mL \cdot g^{-1}$
Substrate[x]					
PBC	334.5 a[w] ± 10.0	42.0 a ± 1.4	376.5 a ± 9.9	0.13 a ± 0.01	269 b ± 14.4
PBS	240.8 b ± 20.4	33.6 b ± 3.0	274.5 b ± 22.9	0.14 a ± 0.01	423 a ± 35.0
Irrigation					
PM Replacement	273.6 a ± 15.2	39.1 a ± 2.2	312.8 a ± 16.7	0.14 a ± 0.01	360 a ± 45.2
On Demand	301.7 a ± 29.3	36.5 a ± 3.3	338.2 a ± 32.2	0.12 b ± 0.01	332 a ± 32.0
Control					
AM 0.2 LF	148.8 b ± 5.6	30.6 a ± 1.5	179.4 b ± 7.0	0.21 a ± 0.004	368 a ± 23.6
PM 0.2 LF	201.5 a ± 10.0	33.0 a ± 3.6	234.5 a ± 13.0	0.16 a ± 0.014	325 a ± 16.8

Table 3 continued.

Contrast					
PM Replacement vs. AM 0.2 LF	0.0001	0.0470	0.0001	0.0001	0.8411
PM Replacement vs. PM 0.2 LF	0.0059	0.1417	0.0080	0.1076	0.3892
On Demand vs. AM 0.2 LF	0.0001	0.1598	0.0001	0.0001	0.3826
On Demand vs. PM 0.2 LF	0.0004	0.3955	0.0009	0.0019	0.8508

[z]Root:top ratio = root dry weight ÷ top dry weight.

[y]WUE_p (water use efficiency of productivity) = volume of water retained by substrate (mL) ÷ total plant dry weight (g).

[x]PBC = 8 pine bark : 1 clay (v/v), PBS = 8 pine bark : 1 sand (v/v).

[w]Each mean ± standard error is based on four observations. Means within each column and treatment followed by the same letter are not significantly different as determined by Fisher's Protected LSD at *P*=0.05.

Table 4. Effect of substrate, irrigation treatment, and controls on water use and leaching fraction.

Main effect	Total volume applied	Leaching fraction[z]
	L	
Substrate[y]		
PBC	195 a[x] ± 5.70	0.34 a ± 0.03
PBS	165 b ± 7.84	0.19 b ± 0.03
Irrigation		
PM Replacement	189 a ± 7.14	0.29 a ± 0.05
On Demand	171 a ± 9.27	0.25 a ± 0.03
Control		
AM 0.2 LF	114 a ± 2.22	0.34 a ± 0.02
PM 0.2 LF	115 a ± 2.33	0.15 b ± 0.03
Contrast		
PM Replacement vs. AM 0.2 LF	0.0001	0.1870
PM Replacement vs. PM 0.2 LF	0.0001	0.0051
On Demand vs. AM 0.2 LF	0.0001	0.0338
On Demand vs. PM 0.2 LF	0.0001	0.0361

Table 4 continued.

[z]Leaching fraction = water volume applied ÷ water volume leached.

[y]PBC = 8 pine bark : 1 clay (v/v), PBS = 8 pine bark : 1 sand (v/v).

[x]Each mean ± standard error is based on four observations. Means within each column and treatment followed by the same letter are not significantly different as determined by Fisher's Protected LSD at P=0.05.

Table 5. Average values for start time, stop time, run time, number of cycles, weight gain, and TAAR of treatments.

Treatment	Start time	Stop time	Run time	Number of cycles	Weight gain per cycle	Weight gain per day	TAAR[z]
	HR	HR	Min		g	g	mL/min
June 2006							
PBC[y] On Demand	1026	1614	348	1.7	389	724	2.7 a
PBS On Demand	1127	1632	410	2.0	410	820	3.1 a
PBC PM Replacement	1200[x]	1800	360	3.0	206	618	1.7 b
PBS PM Replacement	1200[x]	1800	360	3.0	201	589	1.6 b
PBS AM 0.2 LF	0100[x]	0700	360	3.0	319	956	2.8 a
PBS PM 0.2 LF	0100[x]	0700	360	3.0	360	1079	2.9 a
July 2006							
PBC On Demand	0938	1811	512	3.9	408	1575	3.4 bc
PBS On Demand	1053	1749	416	3.4	449	1516	3.8 b
PBC PM Replacement	1200	1800	360	3.0	655	1965	5.5 a

Table 5 continued.

PBS PM Replacement	1200	1800	360	3.0	471	1387	4.0 b
PBS AM 0.2 LF	0100	0700	360	3.0	336	1008	2.8 d
PBS PM 0.2 LF	0100	0700	360	3.0	369	1106	3.0 cd
<u>August 2006</u>							
PBC On Demand	0810	1917	667	7.3	431	3161	5.0 c
PBS On Demand	0923	1817	535	5.3	456	2436	4.6 c
PBC PM Replacement	1200	1800	360	3.0	994	2983	8.3 a
PBS PM Replacement	1200	1800	360	3.0	742	2225	6.1 b
PBS AM 0.2 LF	0100	0700	360	3.0	364	1091	3.0 d
PBS PM 0.2 LF	0100	0700	360	3.0	422	1265	3.0 d
<u>September 2006</u>							
PBC On Demand	0921	1827	9:06	7.4	484	3474	6.5 b
PBS On Demand	1023	1739	7:16	6.1	477	2900	6.9 ab

Table 5 continued.

PBC PM Replacement	1200	1800	360	3.0	947	2840	7.9 a
PBS PM Replacement	1200	1800	360	3.0	762	2127	6.3 b
PBS AM 0.2 LF	0100	0700	360	3.0	376	1128	3.0 c
PBS PM 0.2 LF	0100	0700	360	3.0	448	1345	3.7 c

[z]Time Averaged Application Rate = water applied daily (mL) ÷ application duration time (min)

[y]PBC = 8 pine bark : 1 clay (by vol.); PBS = 8 pine bark : 1 sand (by vol.).

[x]As dictated by treatment selection.

Table 6. Effect of substrate, irrigation treatment, and controls on substrate solution pH.

Treatment	Days after initiation						
	12	25	37	56	67	79	95
Substrate							
PBC[z]	5.7 a[y] ± 0.05	5.4 a ± 0.06	5.7 a ± 0.05	5.8 a ± 0.12	6.1 a ± 0.03	6.1 a ± 0.08	5.6 a ± 0.04
PBS	5.4 b ± 0.06	5.0 b ± 0.09	5.3 b ± 0.08	5.4 b ± 0.13	5.4 b ± 0.09	5.4 b ± 0.15	5.2 b ± 0.19
Irrigation							
PM Replacement	5.5 b ± 0.06	5.1 b ± 0.12	5.6 a ± 0.09	5.8 a ± 0.13	5.7 a ± 0.14	5.8 a ± 0.18	5.4 a ± 0.10
On Demand	5.6 a ± 0.07	5.3 a ± 0.08	5.5 a ± 0.12	5.4 b ± 0.12	5.7 a ± 0.17	5.7 a ± 0.17	5.4 a ± 0.13
Control							
AM 0.2 LF	5.6 a ± 0.13	5.1 a ± 0.13	5.6 a ± 0.10	5.2 a ± 0.13	5.3 a ±0.06	5.4 a ± 0.10	5.2 a ± 0.19
PM 0.2 LF	5.4 a ± 0.07	5.1 a ± 0.20	5.3 a ± 0.15	5.5 a ± 0.31	5.3 a ± 0.24	5.4 a ± 0.16	5.4 a ± 0.13

Table 6 continued.

Contrast							
PM Replacement vs. AM 0.2 LF	0.3925	0.5388	0.8160	0.0016	0.0046	0.0248	0.2056
PM Replacement vs. PM 0.2 LF	0.3502	0.7337	0.0219	0.0814	0.0072	0.0186	0.9599
On Demand vs. AM 0.2 LF	0.3639	0.1352	0.3301	0.1165	0.0168	0.1267	0.1874
On Demand vs. PM 0.2 LF	0.0140	0.0220	0.0940	0.7714	0.0107	0.0985	0.9141

[z]PBC = 8 pine bark : 1 clay (v/v), PBS = 8 pine bark : 1 sand (v/v).

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[y]Each mean ± standard error is based on four observations. Means within each column and treatment followed by the same letter are not significantly different as determined by Fisher's Protected LSD at *P*=0.05.

Table 7. Effect of substrate, irrigation treatment, and controls on substrate solution EC ($mS \cdot m^{-1}$).

Treatment	Days after initiation						
	12	25	37	56	67	79	95
Substrate[z]							
PBC	0.23 a[y] ± 0.03	0.76 a ± 0.11	0.43 a ± 0.04	0.41 b ± 0.05	0.34 b ± 0.02	0.43 a ± 0.04	0.28 a ± 0.02
PBS	0.31a ± 0.03	0.74 a ± 0.05	0.50 a ± 0.05	0.58 a ± 0.05	0.54 a ± 0.05	0.61 a ± 0.08	0.31 a ± 0.02
Irrigation							
PM Replacement	0.32 a ± 0.02	0.98 a ± 0.06	0.44 a ± 0.03	0.34 b ± 0.03	0.38 a ± 0.03	0.50 a ± 0.06	0.33 a ± 0.03
On-Demand	0.18 b ± 0.02	0.56 b ± 0.08	0.48 a ± 0.05	0.61 a ± 0.04	0.45 a ± 0.05	0.50 a ± 0.05	0.28 a ± 0.03
Control							
AM 0.2 LF	0.26 a ± 0.05	0.64 b ± 0.06	0.30 b ± 0.02	0.48 a ± 0.06	0.48 a ± 0.03	0.51 a ± 0.06	0.25 a ± 0.01
PM 0.2 LF	0.44 a ± 0.08	0.77 a ± 0.06	0.71 a ± 0.01	0.74 a ± 0.11	0.70 a ± 0.14	0.71 a ± 0.16	0.32 a ± 0.02

Table 7 continued.

Contrast							
PM Replacement vs. AM 0.2 LF	0.2634	0.0065	0.0339	0.0745	0.2497	0.9675	0.0534
PM Replacement vs. PM 0.2 LF	0.0476	0.0715	0.0006	0.0001	0.0015	0.0947	0.6331
On Demand vs. AM 0.2 LF	0.1690	0.4319	0.0099	0.0811	0.7891	0.9291	0.4953
On Demand vs. PM 0.2 LF	0.0003	0.0608	0.0020	0.0679	0.0102	0.0867	0.3770

[z]PBC = 8 pine bark : 1 clay (v/v), PBS = 8 pine bark : 1 sand (v/v).

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[y]Each mean ± standard error is based on four observations. Means within each column and treatment followed by the same letter are not significantly different as determined by Fisher's Protected LSD at *P*=0.05.

Table 8. Effect of irrigation treatment on net photosynthesis (P_n) stomatal conductance (g_s) and water use efficiency of photosynthesis (WUE_{Pn}) of Cotoneaster dammeri 'Skogholm' at 92 days after initiation.

Time	Treatment	Ps ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	g_s ($\mu mol \cdot m^{-2} \cdot s^{-1}$)	WUE_{Pn} [z] ($mmol\ water \cdot \mu mol\ CO_2^{-1}$)
1000 HR	Irrigation			
	PM Replacement	8.7 a[y] ± 1.09	0.34 a ± 0.02	0.04 a ± 0.006
	On Demand	10.4 a ± 0.69	0.40 a ± 0.03	0.04 a ± 0.004
	Control			
	AM 0.2 LF	12.6 a ± 1.14	0.37 a ± 0.04	0.03 a ± 0.01
	PM 0.2 LF	8.2 a ± 0.79	0.31 b ± 0.04	0.04 a ± 0.003
1300 HR	Irrigation			
	PM Replacement	5.8 a ± 1.11	0.34 a ± 0.01	0.07 a ± 0.01
	On Demand	7.6 a ± 1.20	0.40 a ± 0.02	0.06 a ± 0.01
	Control			

Table 8 continued.

	AM 0.2 LF	10.8 a ± 2.06	0.39 a ± 0.06	0.04 a ± 0.003
	PM 0.2 LF	5.2 b ± 1.31	0.30 a ± 0.03	0.07 a ± 0.02
<u>Contrast</u>				
1000 HR	PM Replacement vs. AM 0.2 LF	0.0144	0.4863	0.1519
	PM Replacement vs. PM 0.2 LF	0.0073	0.2228	0.4590
	On Demand vs. AM 0.2 LF	0.2318	0.2603	0.7087
	On Demand vs. PM 0.2 LF	0.1294	0.1058	0.7087
1300 HR	PM Replacement vs. AM 0.2 LF	0.0324	0.2467	0.1147
	PM Replacement vs. PM 0.2 LF	0.0187	0.0690	0.0675
	On Demand vs. AM 0.2 LF	0.3908	0.2202	0.5478

Table 8 continued.

On Demand vs. PM 0.2 LF	0.2576	0.0604	0.3719

[z]$WUE_{pn} = g_s \div P_n$

[y]Means within each variable and time followed by the same letter are not significantly different as determined by Fisher's LSD at *P* = 0.05.

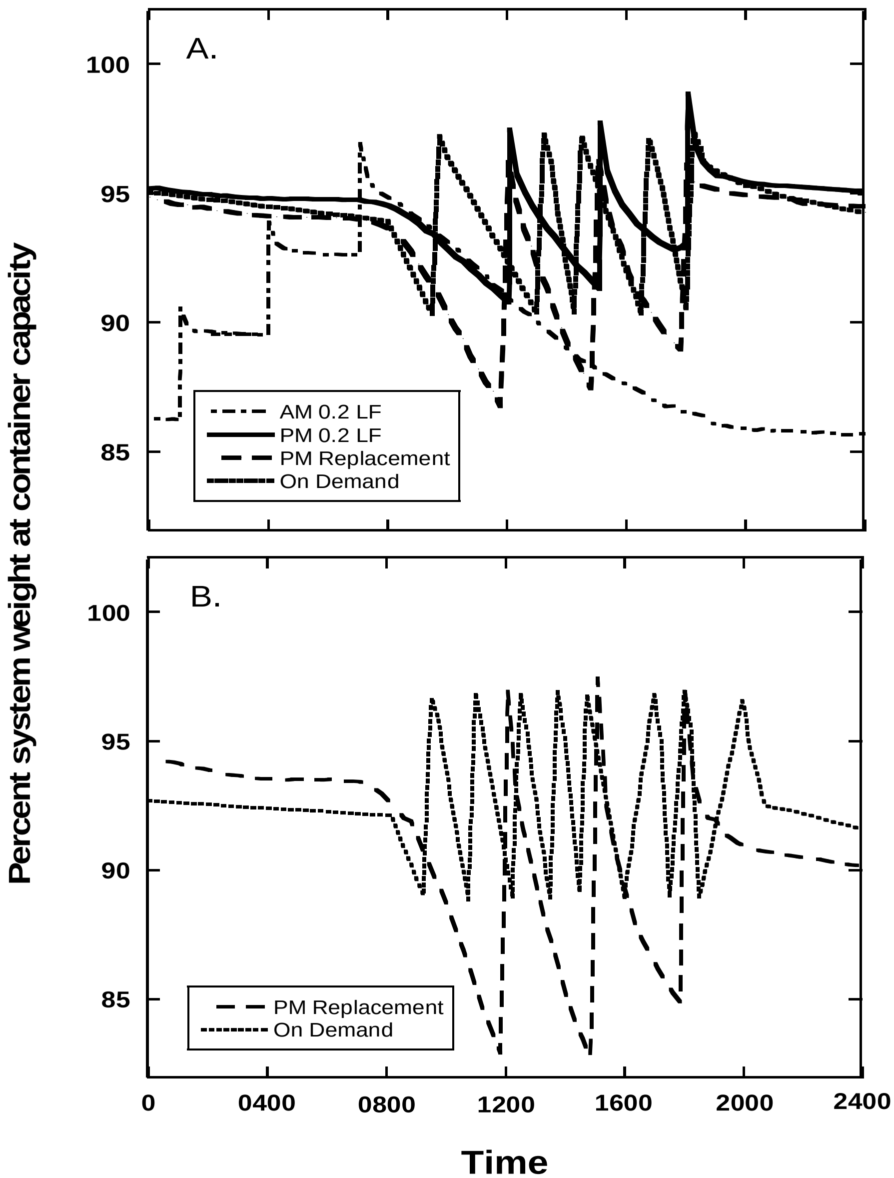

Figure 1. Water gain and evapotranspiration of Skogholm cotoneaster grown over 24 hours with two substrates (A. Pine bark:sand; B. Pine bark:clay) and four irrigation regimes (AM 0.2 LF irrigates at 0100, 0400, 0700 HR; PM 0.2 LF irrigates at 1200, 1400, 1800 HR; PM Replacement replaces all water lost up to 98% CC at 1200, 1400, 1800 HR; On Demand replaces all water lost when system drops below 92% up to 98% CC) on 8 August 2006.

Chapter 2

Comparison of Water management in container-grown nursery crops using leaching fraction or weight-based on demand irrigation control.

(In the format appropriate for submission to the

Journal of Environmental Horticulture)

Alison E. Prehn

Department of Horticultural Science, North Carolina State University,

Raleigh, NC 27695

ABSTRACT

Water management should be the core of container nursery production as it is linked directly to both water and nutrient use efficiency and ultimately, environmental impact. Gravitational techniques have been used to determine substrate moisture. However, there has been little work done with automation of a gravitational system in a nursery setting. In this study the gravimetric technique was used via a load cell/computer interface to determine irrigation volume and time of water application. The goal of this experiment was to determine some maximum and minimum irrigation parameters to make this system more practical and efficient, and to reestablish the differences between a conventional cyclic PM 0.2 LF irrigation regime and a regime using the gravimetric technique. *Cotoneaster dammeri* 'Skoghom' was grown in 14 L (#5) containers with an 8:1 pine bark:sand mixture. The treatments were: an industry control that was irrigated cyclically at 1200, 1500, and 1800 HR to maintain a 0.2 LF (PM 0.2 LF); and a gravimetric treatment that irrigated when container capacity (CC) dropped below 94% and returned the CC to 98%. These percentages were lowered over the course of the season, always in a 4% spread, to maintain <0.15 LF (On Demand). Plant dry weight and root:top ratio were unaffected by the treatments. Total irrigation volume applied per container was not significantly affected by treatment. When daily irrigation volume was examined within early, mid, and late season daily irrigation volume, PM 0.2 LF applied 42% more water than On Demand in the early season, On Demand applied 73% more than PM 0.2 LF in mid season, and irrigation volume was similar by the end of the season. Number of irrigation cycles were similar until the end of the study when On Demand ran up to seven times a day. PM 0.2 LF had a greater WUE_p (gram of dry weight produced per mL of water retained in the substrate). Time averaged application rate

for On Demand was always lower than PM 0.2 LF resulting in a LF of 0.6 compared to 0.14 LF for PM 0.2 LF.

SIGNIFICANCE TO NURSERY INDUSTRY

Irrigating *Cotoneaster dammeri* 'Skoghom' using the gravimetric technique produced an equivalent plant compared to the cotoneaster produced with a 0.2 leaching fraction applied cyclically at 1200, 1500, and 1800 HR. Concurrently, the gravimetric technique maintained an average leaching fraction of 0.06. This is an improvement over typical cyclic irrigation regimes and these results cannot be obtained by grower-monitoring alone without significant labor cost. The gravimetric technique is ideal because it requires no calibration and no special skills to setup or operate. In addition, it directly measures the quantity of water lost since the last irrigation thus requiring no data interpretation.

INTRODUCTION

Water restrictions are becoming more prevalent throughout the horticultural world causing growers to rethink current water management strategies. Soon, to be competitive in their industry, growers will be required to make efficient water management the core of container-grown crop production.

Currently, irrigation of container-grown nursery crops is almost always an inefficient practice (Warren and Bilderback, 2005). Most container nurseries in the southeastern United States maintain ≥ 0.5 leaching fraction [LF = irrigation volume leached (mL) ÷ irrigation volume applied (mL)] (Ted Bilderback Ph.D, professor and nursery specialist, North Carolina State University, personal commun.) resulting in less than 50% of the water applied being used by the plant. As water is a finite resource, every effort should be made to maximize a plant's use of all water applied to a container. Even though most nurseries have some type of a recycling system for water, the more water they must pump and treat throughout the nursery, the higher their overall costs. To prevent the detrimental effects limited water can have on plant production, it is important these irrigation techniques improve water use efficiency while continuing to maximize crop growth.

Best Management Practices (BMPs) have been created to give growers guidelines and strategies to minimize and more effectively use vital resources. BMPs include use of controlled release fertilizers (CRFs), retention ponds to recycle irrigation water, soilless substrates with a high water-retaining capacity, and implementation of practices such as cyclic irrigation and reduced LF which minimize run-off (Chen et al., 2001; Sharma et al;. 2008; Yeager et al., 2007).

BMPs for the southeastern United States currently recommend an 80% to 90% water application efficiency {WAE = [(volume applied - volume leached) ÷ volume applied] x 100} to ensure proper rewetting of the substrate, with LF not to exceed 0.25. Unfortunately, for many growers how much water to apply (volume) and when to apply it (timing) are based on work hours and irrigation system limitations (pump run time). To apply the proper volume requires weekly to daily monitoring during the growing season. Without proper monitoring it is difficult to know precisely what is going on in the substrate moisture environment throughout the day.

New methods of irrigation monitoring and control are introduced to the nursery industry on a regular basis, however few are adopted due to unreliable accuracy, required training for use, difficulty of use, complexity of data interpretation, and high cost. The most recently tested methods use tensiometry and time domain reflectometry (TDR) to monitor substrate water levels. However, there are numerous problems with these systems including calibration required for each substrate, limited operating range, response lag time, continuous maintenance, and the fact that probes must maintain good contact with the substrate. These methods overlook the age-old method of gravimetric determination. The simplest way to determine water loss is to weigh the container (container, substrate, and plant), where 1 g of weight is equivalent to 1 ml of water. The difference in weight from CC describes the milliliters (fl oz) of water needed to return the container to 100% CC.

The gravimetric technique is ideal because it requires no calibration and no special skills to set up or operate. It directly measures the quantity of water loss since the last irrigation thus requiring no data interpretation. Knowing this information the grower can determine how much and when to irrigate to replace the available water needed to eliminate diurnal plant stress. In this experiment a load cell was used to weigh containers and add back precise volumes of water. The objective of this research was to compare a traditional schedule of irrigation, in which volume applied was determined using LF, to an automated gravitational method of irrigation control.

MATERIALS AND METHODS

Experimental design. There were two treatments: an 8:1 pine bark to sand ratio (by vol.) substrate irrigated at 1200, 1500, and 1800 HR to maintain a 0.2 LF (served as the industry control and hereafter referred to as PM 0.2 LF), and the same pine bark:sand substrate irrigated to return the substrate to 98% CC when the water content reached 94% of CC as determined by weight regardless of time (hereafter referred to as On Demand). As newly planted cuttings require frequent irrigation to ensure survival, the upper and lower CC limits in the On Demand treatment were initially set at these high values. The irrigation could maintain adequate water in the upper portion of the substrate for the small root sytems while maintaining a minimum LF. As plants grew and evapotranspiration increased the upper and lower CC limits were decreased, always maintaining a 4% spread. Seventy-nine days after planting (DAP), the 98% to 94% CC was reduced to 96% to 92% CC, and at 99 DAP this was reduced to 94% to 90% CC. This was done in an attempt to maintain adequate water in the substrate as the plants grew while concurrently reducing the LF.

This experiment was conducted on a gravel pad at the Horticulture Field Lab (lat. 35°47'37'N, long. -78°41'59'W), North Carolina State University, Raleigh, in a randomized complete block design with four blocks and seven containers per replication. Uniform rooted stem cuttings of *Cotoneaster dammeri* C.K. Schneid. ‘Skogholm’ were potted on April 19, 2007 into black, plastic 14 L (#5) containers (C-2000, Nursery Supplies Inc., Chambersburg, PA). The substrate was a course builder’s sand and local North Carolina pine bark with a bulk density of 33.3 lbs ft^3, 77% total porosity, 48% container capacity, 29% air space, 27% unavailable water, and 21% available water.

The substrate was amended with dolomitic limestone [$CaMg(CO_3)_2$] and a micronutrient fertilizer (Micromax, Scotts Company, Marysville, OH) at a rate of 1.8 $kg{\cdot}m^{-3}$ (0.11 lb/ft^3). After planting, containers were topdressed according to the medium label of 71.2 g (2.5 oz) 16N-2.6P-9.0K (16-6-11 six month CRF, Harrell’s, Lakeland, FL).

Each gravel covered plot [8 x 1 m (26.3 x 3.3 ft)] was underlain with corrugated plastic at a 2% slope for directing all leachate from each plot to a 19 L (5.0 gal) collection vessel. Influent volumes from irrigation water applied via pressure compensated spray stakes

[Acu-Spray Stick; Wade Mfg. Co., Fresno, Calif. (200 mL min^{-1}) (6.8 fl. oz. min^{-1})] were measured as the volume collected in a 4 L (1.0 gal) vessel from a spray stake on each plot. Volumes of irrigation water applied (influent) and leached (effluent) for each plot were measured daily, and LF was calculated. Influent volumes were adjusted daily to maintain the 0.2 LF for each plot in the PM 0.2 LF treatment. Data were compiled to determine cumulative influent volume per container and cumulative effluent volume per container. Cumulative water volume retained per container was calculated as the sum of the daily difference between influent and effluent volumes per container. Effluent volumes were measured following rain events with <0.64 cm (0.25 in) of rain, however, data collected on these days were not used in the cumulative influent and effluent calculations. From these data, water use efficiency of productivity (WUE_P = total irrigation volume retained in substrate ÷ total plant dry weight) and time averaged application rate (TAAR = water applied day ÷ application duration time) were calculated.

Within each treatment and block, one plant was positioned on a load cell (total of 16). Real time monitoring of container weight (plant + substrate + container) was performed using a low profile, two-beam single aluminum (Al) point load cell with a 30 kg (66.1 lb) capacity (± 0.02% error) (Model RL 1042, Tedea-Huntleigh Inc, Covina, CA). The load cell was mounted between two 15 cm x 15 cm, (5.9 in x 5.9 in) 0.6 cm (0.24 in) thick square Al plates. One 0.6 cm (0.24 in) thick Al spacer was attached between the top and bottom plates and the load cell to keep debris out. The top surface area was expanded with a 23 x 23 cm (9.1 in x 9.1 in) square, 3 mm (0.12 in) thick Al plate. The load cells were connected to a CR3000 Micrologger® via an AM32 multiplexer (Campbell Scientific, Logan, Utah). Weight was recorded every 15 minutes, and every 10 seconds when the irrigation was running. Container capacity was determined by saturating the containers at approximately every 3 weeks. Saturation was achieved by placing the container from the load cell into a 20 L (5 gal) bucket which was filled with water at approximately 1800 HR. When the substrate was fully saturated, after approximately 2 hr (as evidenced by a glossy sheen of water at the substrate surface), the containers were placed on the load cells and allowed to drain until 0000 HR (12 am) the following morning. At 0000 HR the computer recorded weights for each of the 16 containers, and this was assumed to be equivalent to CC.

Substrate temperatures were measured at two locations in one container in every replication (total of 8 thermocouples per treatment) for the entire study. The copper-constantan thermocouples were positioned in the substrate ≈8 cm (3.2 in) down the container profile 2.5 cm (1 in) from the container wall on the southern and northern exposure in each container. Thermocouples were connected to the CR3000 micrologger® via an AM32 multiplexer (Campbell Scientific). Temperature was recorded every 5 min and averaged over each 60-min interval. Maximum, minimum, and average temperature along with time of maximum and time of minimum were recorded every 60 min.

Electrical conductivity (EC) and pH of the substrate solution were measured every 3 weeks via the pour-through nutrient extraction procedure (Wright, 1986). Net photosynthesis (P_n) and stomatal conductance (g_s) were measured on July 24, 2007. One plant from each of the replications was measured between 1030 and 1130 HR. The measurements were taken using a portable photosynthesis system containing a LI-6400 open, portable gas exchange system with a LI-6400-05 conifer chamber (LI-COR, Lincoln, NE). Measurements were conducted on the intact terminal 5 cm (2 in) of stem with approximately 5 fully expanded leaves [5.55 cm^2 ± 0.29 SE (2.2 in^2)] under natural light in which photosynthetic active radiation remained >1600 µmol mol^{-1}. These data were used to calculate water use efficiency of photosynthesis (WUE_{Pn} = CO_2 assimilation ÷ stomatal conductance).

The experiment was initiated on June 7, 2007 and terminated after 95 days. At termination, tops (aerial tissue) were removed from two plants from each plot (total of 8 containers per treatment). Roots were placed over a screen and washed with a high pressure water stream to remove substrate. Tops and roots were dried at 65C (149F) until reaching a stable weight and weighed. Root:top ratio (RTR= root dry weight ÷ top dry weight) was determined from dry weights.

After drying, the tops and roots were first ground using a Model 4 bench, 1 HP Wiley Mill® (Thomas Scientific, Swedesboro, NJ), to pass ≤ 6mm (0.24 in) screen and then through a Foss Tecator Cyclotec 1093 sample mill (Analytical Instruments, LLC, Golden Valley, MN) to pass ≤ 0.5 mm (0.02 in) screen. Roots and tops were analyzed for nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), molybdenum (Mo), and sodium (Na) by the North Carolina Department of Agriculture, Agronomic Division. Total N concentrations were determined by oxygen combustion with an elemental analyzer (NA 1500; CE Elantech Instruments, Milan, Italy) (Campbell and Plank, 1992). Phosphorus, K, Ca, Mg, S, Fe, Mn, Zn, Cu, B, and Na concentrations were determined by EPA Method 200.7 with an ICP spectrophotometer (Optima 3300 DV ICP Emission Spectrometer; Perkin Elmer Corporation, Wellesley, MA.), following open-vessel HNO_3 digestion in a microwave digestion system (CEM Corp., Matthews, NC) (Donohue and Aho, 1992).

Statistical analysis. All variables were analyzed using analysis of variance (ANOVA) Proc GLM in SAS version 9.01 (SAS Inst. Inc., Cary, NC). Treatment comparisons were made by F test, $P \leq 0.05$.

RESULTS AND DISCUSSION

Plant Response. Top dry weight, root dry weight, total dry weight, and RTR were unaffected by the treatments (Table 1). This is in contrast to an earlier study where Skogholm cotonester grown with On Demand irrigation had a significantly larger top and total dry weight than PM 0.2 LF (Prehn, 2008)

Water Use. Total irrigation volume applied per container over the life of the study was not significantly affected by the treatments (Table 2). However, when examined as daily water volume (weight gained) per container in early, midway and late in the season the treatments significantly affected daily irrigation volume (Table 3). Early in the study (June), when evapotranspiration was the lowest, On Demand applied a daily average of 0.5 L (0.14 gal) per container, whereas PM 0.2 LF used 0.9 L (0.25 gal), 42% more water. This demonstrates the power of weight-based application in contrast to a fixed LF. As the plants grew and temperature increased which increased evapotranspiration, On Demand increased to an average daily application of 2.1 L (0.55 gal) in mid-season (July), an increase of 74% compared to only a 39%, 1.5 L (0.4 gal), increase for 0.2 LF. By late season (August) both irrigation treatments were applying similar daily irrigation volumes. The number of cycles per day were remarkably similar early and midway in the study, whereas by late in the study when evapotranspiration was at a maximum, On Demand irrigated seven times or more a day to remain within the given upper and lower CC limits. As the number of cycles increased throughout the study, the first irrigation event in the On Demand treatment initiated earlier in the day. Early in the Season (June) the first irrigation event initiated at 1155 HR for On-Demand versus the fixed 1200 HR for PM 0.2 LF. Midway in the study the first irrigation event started around 0953 HR and by late in the study was at 0738 HR for On Demand. In contrast, the last irrigation event was similar for On Demand and PM 0.2 LF midway (1804 HR versus 1800 HR) and late in the study (1909 HR versus 1800 HR). The combination of these events (total run time, number of cycles, total weight gain per day) also decreased the average TAAR throughout the study for On Demand versus PM 0.2 LF. In early, mid, and late season TAAR was significantly less for On Demand compared to PM 0.2 LF (a smaller TAAR is more desirable).

Leaching fraction was significantly affected by treatments, with On Demand averaging 0.06 and PM 0.2 LF averaging 0.14 for the entire study (Table 2). This shows that equivalent growth can be produced with drastically reduced LF compared to the recommended 0.2 LF. However, it would be very difficult for a grower to maintain this very low LF without some form of real-time substrate moisture monitoring equipment. It would be very probable that plants would experience water stress with this low LF with human monitoring alone (personal experience).

Water application efficiency [WAE = 100 - (irrigation volume leached - irrigation volume applied) x 100)] averaged 94% for On Demand versus 85% for PM 0.2 LF. This very high level of WAE is a result of the decreased TAAR produced by On Demand compared to PM 0.2 LF (Table 3). According to Lamack and Niemiera (1993), low TAAR is highly correlated with high WAE. Low TAAR values and resulting high WAE should be a target of every irrigation operator (Warren and Bilderback, 2005), and therefore gravitational

On Demand irrigation is a further improvement on the cyclic method of irrigation application.

Interestingly, the previously discussed results produced significantly different WUE_p (Table 2). On Demand required 139 more mL (0.04 gal) of water to produce one g of dry mass, which is 19% more than PM 0.2 LF. By maintaining what would appear to be a more consistent substrate water environment, evapotranspiration increased without increasing plant biomass. This was surprising.

Photosynthesis and Stomatal Conductance. Even though WUE was significantly affected by the treatments, this was not expressed in P_n, g_s or WUE_{Pn} as they were unaffected (Table 4). It is not unusual to find no differences when P_n and g_s are measured on individual leaves (van Iersel, 2003) and the quantitative larger values for On Demand found in Table 4 may have resulted in higher water losses when expressed on a whole plant basis.

EC and pH. Electrical conductivity was higher in every instance in the On Demand treatment but was only significantly greater than PM 0.2 LF at 48 DAI (Table 5). This was probably due to the decreased LF allowing more salts to remain in the substrate. Even so, all values were within the acceptable range, and are even closer to desirable EC levels for containers than plants irrigated in a more traditional manner (Yeager et al., 2007). There were no significant differences or trends in substrate pH.

Nutrients. There were no significant differences among macronutrient concentrations in the roots of either of the treatments (Table 6). There were, however, significant differences among P and K macronutrient concentrations in plant tops. There was less P and K in the plant tissue of PM 0.2 LF (by 26% and 21%, respectively) than On Demand. Phosporous and K leach readily from containerized plants (Broshat, 1995) and so the reduced LF for On

Demand may have produced these results. In this case, with an average LF of only 0.06, On Demand was able to retain more P and K in the substrate and it was therefore more available for uptake by the plants. Nitrogen is also readily leached, however, there was no difference in plant top concentration. None of the other top nutrient concentrations differed between treatments.

Substrate temperature. Substrate temperatures between the two treatments differed during some parts of the day over the entire experiment (Fig. 1). At 49 DAI, maximum temperature was greater for On Demand at 0300 HR to 0700 HR. This is when the last irrigation event for both treatments started at about the same time, so it is difficult to explain why PM 0.2 LF was cooler during the early morning hours, except that the last irrigation event the day before may have been longer for the PM 0.2 LF as run-time was based on time rather than weight. The average temperatures were significantly different at 0500 HR to 0700 HR, when PM 0.2 LF was cooler, and 1000 HR to 1200 HR, when On Demand was cooler. On day 54 the maximum (1100 HR) temperatures were significantly greater for PM 0.2 LF. Thus, it appears that On Demand did maintain lower substrate temperatures throughout the day. This decreased substrate temperature is believed to be a result of the increased number of irrigation cycles and the increased total run time. Even though the decreased substrate temperature did not result in increased growth of Skogholm cotoneaster there may be more heat sensitive species that would respond positively to the decreased substrate temperature.

In conclusion, On Demand gravitational irrigation with can reduce the total leaching fraction to less than 0.1. Dry weight between On Demand and traditional PM irrigation did not result in different-sized plants, contrary to the findings in Prehn, 2008, where On Demand irrigation grew a much larger plant. Time-averaged application rate was better (less) for On Demand irrigation at all points in the season, and also kept the substrate temperature cooler for the entire study. All of these benefits come with reduced need for irrigation personnel, no data interpretation, special skills, or system calibration. We believe the gravitational method of irrigation has great potential and research is continuing in this area using different plants, substrates, and overhead irrigation to make it an even more superior irrigation method.

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Table 1. Effect of treatments on plant dry weight (g) and root:top ratio[z].

Treatment	Top dry weight	Root dry weight	Total dry weight	Root:top ratio
		g		
On Demand	90.5[y] ± 7.9	10.2 ± 0.9	100.7 ± 8.7	0.11 ± 0.01
PM 0.2 LF	96.7 ± 3.8	11.7 ± 0.8	108.4 ± 4.4	0.12 ± 0.01
Significance	0.684[w]	0.426	0.650	0.437

[z]Root:top ratio = root dry weight ÷ top dry weight.

[y]Each mean ± standard error is based on four observations.

[w]*P*-value

Table 2. Effect of treatments on total water volume applied (L), leaching fraction, and water use efficiency of productivity (WUE_p).

Treatment	Total volume applied	Leaching fraction[z]	WUE_p[y]
	L		mL g^{-1}
On Demand	77.3[x] ± 1.1	0.06 ± 0.01	715.6 ± 2.8
PM 0.2 LF	74.1 ± 1.6	0.14 ± 0.02	577.0 ± 1.5
Significance	0.772[w]	0.010	0.004

[z]Leaching fraction = water leached (L) ÷ water applied (L).

[y]WUE_p = total irrigation volume retained in substrate (mL) ÷ total plant dry weight (g).

[x]Each mean ± standard error is based on four observations.

[w]*P*-value

Table 3. Average values for start time, stop time, water applied, run time, number of cycles, weight gain, and TAAR of two irrigation treatments.

Treatment	Start time	Stop time	Total run time	Number of cycles	Weight gain per cycle	Weight gain per day	TAAR[z]
	HR	HR	min		mL	mL	mL min^{-1}
				Early Season (June)			
PM 0.2 LF	1200[y]	1800	360	3.0	311	922	2.7 a[X]
On Demand	1155	1652	296	2.0	271	544	1.6 b
				Midseason (July)			
PM 0.2 LF	1200[y]	1800	360	3.0	504	1510	4.1 a
On Demand	0953	1804	613	3.5	315	2081	2.2 b
				Late season (August)			
PM 0.2 LF	1200[y]	1800	360	3.0	670	2009	5.4 a
On Demand	0738	1909	811	7.5	308	2278	3.3 b

[z]Time averaged application rate = water applied daily (mL) ÷ total run time (min).

[y]Dictated by treatment selection.

[x]Means within a column and season not followed by the same letter are significantly different as determined by F test, $P \leq 0.05$.

Table 4. Effect of irrigation treatment on net photosynthesis (P_n), stomatal conductance (g_s) and water use efficiency of photosynthesis (WUE $_{Pn}$) of *Cotoneaster dammeri* 'Skogholm' at 1000 HR 47 days after initiation.

Treatment	P_n	g_s	WUE_{Pn} [z]
	($\mu mol \cdot m^{-2} \cdot s^{-1}$)	($\mu mol \cdot m^{-2} \cdot s^{-1}$)	(mmol H_20 $\cdot \mu mol$ CO_2^{-1})
On Demand	17.0 ± 1.54[y]	0.25 ± 0.05	0.02 ± 0.003
PM 0.2 LF	15.1 ± 0.52	0.22 ± 0.01	0.01 ± 0.000
Significance	0.318[x]	0.351	0.134

[z] $WUE_{pn} = g_s \div P_n$

[y] Each mean ± standard error is based on four observations.

[x] *P*-value.

Table 5. Effect of treatments on substrate pH and electrical conductivity (EC) at 13, 29, 48, and 64 days after treatment initiation (DAI).

	DAI			
Treatment	13	29	48	64
	pH			
On Demand	6.1[z] ± 0.15	6.1 ± 0.10	5.9 ± 0.10	6.1 ± 0.21
PM 0.2 LF	6.0 ± 0.10	6.3 ± 0.09	5.9 ± 0.10	6.3 ± 0.12
Significance	0.715[y]	0.236	0.715	0.383
	EC (mS)			
On Demand	0.54 a ± 0.07	0.57 a ± 0.09	0.49 a ± 0.03	0.47 a ± 0.07
PM 0.2 LF	0.50 a ± 0.02	0.39 a ± 0.09	0.38 b ± 0.04	0.34 a ± 0.01
Significance	0.542	0.086	0.025	0.111

[z]Each mean ± standard error is based on four observations.

[y]*P*-value

Table 6. Effect on treatments on root and top nutrient concentration.

	Treatment	N	P	K	Ca	Mg	S
		mg·g^{-1}					
Root	PM 0.2 LF	23.6 ± 0.09[z]	1.9 ± 0.002	10.3 ± 0.03	5.3 ± 0.02	2.6 ± 0.01	2.2 ± 0.02
	On Demand	23.3 ± 0.16	2.2 ± 0.02	10.4 ± 0.06	5.7 ± 0.05	2.6 ± 0.02	1.8 ± 0.03
Significance		0.901[y]	0.284	0.890	0.527	0.842	0.376
Top	PM 0.2 LF	14.8 ± 0.26	1.4 ± 0.01	4.5 ± 0.03	2.3 ± 0.02	1.5 ± 0.02	2.1 ± 0.04
	On Demand	14.0 ± 0.22	1.9 ±0.02	5.7 ± 0.03	2.7 ± 0.04	1.6 ± 0.01	2.1 ± 0.04
Significance		0.832	0.048	0.034	0.492	0.677	0.914

Table 6 continued.

Treatment		Fe	Mn	Zn	Cu	B	Na
				$ug \cdot g^{-1}$			$mg \cdot g^{-1}$
Root	PM 0.2 LF	0.01 ± 0.0	0.01 ± 0.0	0.003 ± 0.0	0.001 ± 0.0	0.002 ± 0.0	2.2 ± 0.01
	On Demand	0.01 ± 0.0	0.01 ± 0.0	0.003 ± 0.0	0.001 ± 0.0	0.002 ± 0.0	2.2 ± 0.05
	Significance	0.455[y]	0.315	0.716	0.344	0.626	0.983
Top	PM 0.2 LF	0.02 ± 0.0	0.004 ± 0.0	0.005 ± 0.0	0.002 ± 0.0	0.002 ± 0.00	2.7 ± 0.04
	On Demand	0.01 ± 0.0	0.01 ± 0.0	0.01 ± 0.0	0.002 ± 0.0	0.002 ± 0.0	2.6 ± 0.02
	Significance	0.176	0.405	0.617	0.087	0.467	0.729

[z]Each mean ± standard error is based on four observations.

[y]p-value.

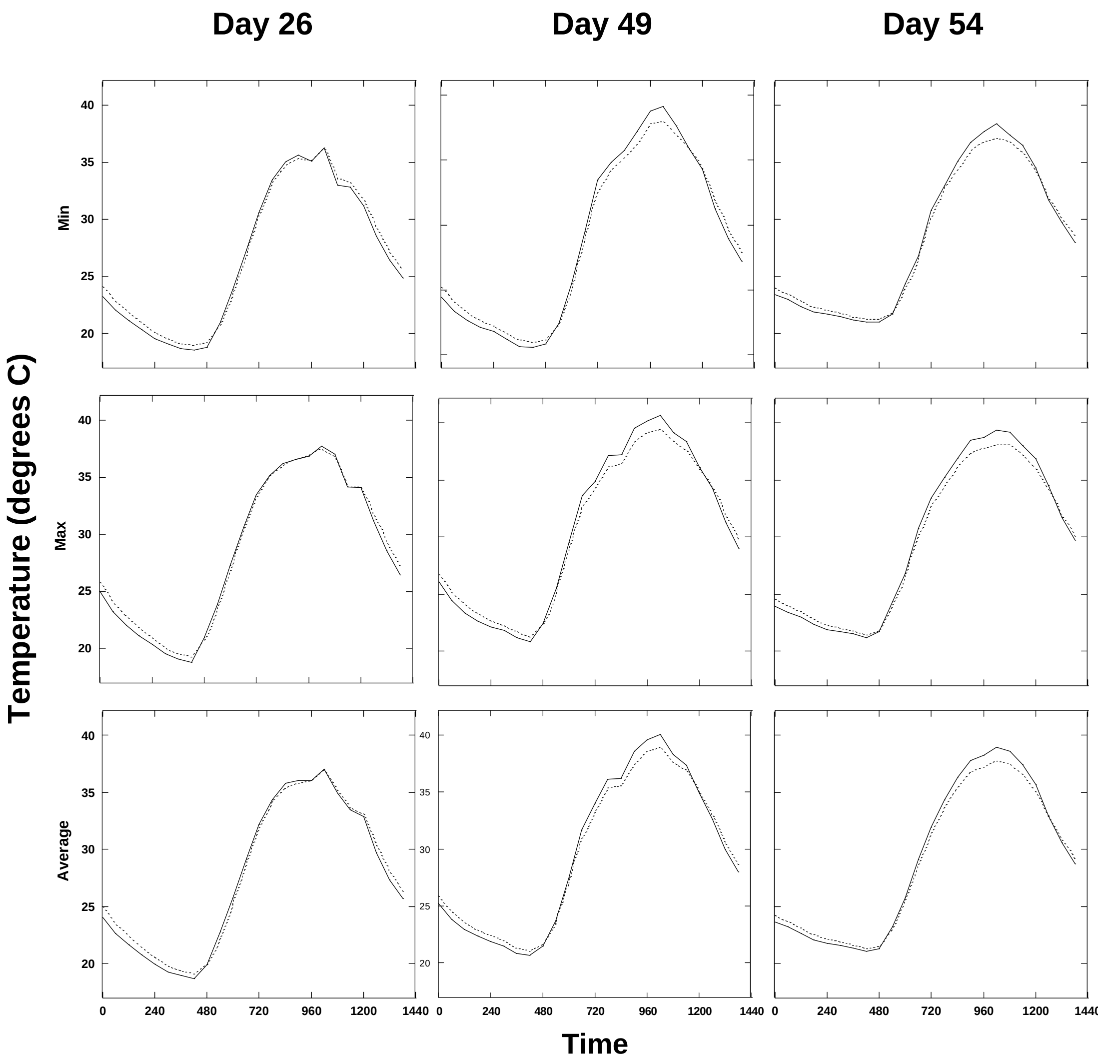

Figure 1. Hourly recorded substrate temperature on selected days (26, 49, 54 DAI) for Skogholm cotoneaster irrigated at 1200, 1500, and 1800 HR (▬▬) or irrigated on demand regardless of time to maintain weight between set upper and lower container capacity parameters (▬ ▬).