This is to certify that the
thesis entitled

IRRIGATION MANAGEMENT IN CONTAINER NURSERY PRODUCTION TO REDUCE WATER USE, RUNOFF, AND OFFSITE MOVEMENT OF AGRICULTURAL CHEMICALS

presented by

Aaron Lynn Warsaw

has been accepted towards fulfillment
of the requirements for the

Master of Science degree in Horticulture

R. Thomas Fernandez
Major Professor's Signature

1/23/09
Date

IRRIGATION MANAGEMENT IN CONTAINER NURSERY PRODUCTION TO REDUCE WATER USE, RUNOFF, AND OFFSITE MOVEMENT OF AGRICULTURAL CHEMICALS

By

Aaron Lynn Warsaw

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Horticulture

2009

ABSTRACT

IRRIGATION MANAGEMENT IN CONTAINER NURSERY PRODUCTION TO REDUCE WATER USE, RUNOFF, AND OFFSITE MOVEMENT OF AGRICULTURAL CHEMICALS

By

Aaron Lynn Warsaw

Irrigation applications based on daily water use (DWU) were compared to a traditional irrigation rate to investigate the effects on plant growth, irrigation and runoff volumes, and nutrient quantities carried in runoff for container-grown woody ornamentals. Plant DWU was determined by measuring the change in substrate volumetric moisture content between irrigations. Irrigation treatments were: 1. a control of 19 mm-ha applied per application; 2. 100% DWU per application; 3. alternating every other application with 100% and 75% DWU; and 4. a three application cycle replacing 100% DWU followed by two applications of 75% DWU. Total irrigation applied by the 3 DWU treatments was reduced 25% to 75% compared to the control depending on treatment and species. Runoff from irrigation applied at 100% and 75% DWU volumes were 66% and 79% less than the control across all measurement days. For all taxa final growth index of DWU treatments was greater than or equal to the control. Relationships of potential evapotranspiration and growth to actual evapotranspiration of *Spiraea fritschiana* Schneid. 'Wilma' show promise for developing a model for irrigation scheduling. The DWU treatments used in this study reduced irrigation volumes, runoff, and nutrient losses compared to a control of 19 mm-ha$\cdot$application^{-1} while producing the same size or larger plants.

ACKNOWLEDGMENTS

I would like to thank my advisor, Tom Fernandez for his continual guidance, support, and friendship. I would also like to thank my committee members Bert Cregg and Jeff Andresen who contributed immensely to the project. I can't thank Bill Chase, Gary Winchell, and the staff at the Horticulture Teaching and Research Center enough for all their help, advice, and for trusting me with their tools. I would like to acknowledge and thank Project GREEEN; The Michigan Department of Agriculture Horticulture Fund; Spring Meadow Nursery, Inc.; Renewed Earth, Inc.; and Harrell's, Inc. for funding and supplying materials for this project. I could have never collected all the data and maintained my field plots without the help of Nicole Haut, Jackie Badder, Amanda Ward, Sara Wiggley, and Mike Konkel who assisted me during the field seasons. I would also like to thank my office mates Matt Ross and Roberto Lopez for making office work fun. Finally, I would like to thank my family back home and all the friends I made in Michigan for supporting me and visiting often, it made leaving home a little easier. I love you all!

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

INTRODUCTION

Container production of woody ornamentals represents a large part of gross sales of the United State's nursery industry. In a survey of 17 states, 88% of the 122 million broadleaf evergreens sold in 2006 were container-grown compared to 11% balled-and-burlapped, and accounted for $739 million in gross sales (Anon., 2007). In 2006, 77% of the 98 million deciduous shrubs sold were container-grown for gross sales of $499 million (Anon., 2007). Michigan was 8th out of the 17 states surveyed with $148 million in sales of nursery crops at wholesale in 2006 (Anon., 2007). Container production accounted for 10% of the 7,135 ha of woody plant material production in 2004, nearly doubling in size from 1999 (Anon., 2005). While the percentage of land area in container production in Michigan may seem low compared to the total land area used to produce woody plant material, container production systems produce more plants per ha than field production. As the container nursery industry continues to expand, growers will be confronted with new challenges, one of which is water management and quality.

Nurseries in close proximity to urban areas face increased competition for ground and surface water resources (Beeson et al., 2004). As a result, water allotted for nursery production will likely decline as demand for potable water from urban areas increases. Beeson et al. (2004) stated that in Florida, permitted water allotments for nurseries have decreased by up to 40% in some areas over the past 12 years. Current regulations and laws already limit water consumption by container nurseries in California, Florida, North Carolina, Oregon, and Texas, and nutrient management laws in Maryland, Delaware, and California limit nutrient concentrations in runoff (Beeson et al., 2004). Legislation has also contributed to making water conservation a key issue for container nurseries in Michigan. Michigan Public Act 148, passed in 2003, requires that heavy water users annually report the volume of water applied and specify conservation practices to the Michigan Department of Agriculture (Anon., 2006). Michigan Public Act 35, passed in 2006, requires that water users also submit an implementation plan for conservation practices to the MDA (Anon., 2006). Heavy water users are defined as operations with the capacity to withdraw 378,500 L (100,000 gal) or more per day for 30 consecutive days, or to extract water at a rate of 265 L (70 gal) per min or greater (Anon., 2006). With future legislation expected to be more stringent, Beeson et al. (2004) have predicted that container nursery access to ground and surface water will significantly decrease in the next decade.

Applying irrigation to replace only the amount of water lost from the container since the previous application is an important concept in water conservation. This requires that the daily water use (DWU) of the plant be known. Scientific information regarding water requirements of the hundreds of species and cultivars of woody ornamentals currently grown is limited. Current irrigation scheduling practices rely on industry estimates of plant water use based on substrate feel, indicator plants, and/or grower experience. In a study by Still and Davies (1993) growers tended to correlate water use of container-grown plants with size, but for some plants their estimates differed from actual water use. For example, *Ligustrum japonicum* Thumb. was rated as a heavy water user by growers prior to the experiment, but actually had one of the lowest total water consumptions of the species in the experiment. This example stresses the importance of knowing actual, not perceived plant water use. It is not uncommon for nurseries to irrigate all plants of the same container size at a common rate each day regardless of water requirement.

The objectives of this research were to: 1. determine DWU and water use efficiency (WUE) of several types of container-grown landscape shrubs to classify them as low, moderate, and high water users; 2. compare plant growth of shrubs irrigated according to a percentage of DWU and a traditional irrigation rate; 3. compare runoff volume and the amount of fertilizers in runoff from DWU scheduled irrigation and a traditional irrigation rate; and 4. evaluate relationships between DWU and meteorological variables for potential use in irrigation scheduling of container-grown landscape shrubs.

Irrigation management based on DWU would have significant impacts regarding water conservation at container nurseries; 1. grouping plants with similar DWU together would reduce water use by minimizing over-watering, 2. reduced leaching would minimize fertilizer losses from containers improving plant nutrition, 3. reduced water use would result in reduced runoff and lower the potential for off-site pollution by nitrates and other agricultural chemicals.

Successful water conservation plans will help protect and preserve water supplies and increase water quality for agricultural production, rural, and urban use by reducing irrigation inputs and runoff. Information regarding plant water use will assist growers in the development and initiation of water conserving practices. By developing irrigation schedules that improve runoff quality and reduce water use, the industry can position itself for future legislation that may impose limits on water extraction.

Literature Cited

Anonymous. 2005. Michigan Rotational Survey: Nursery and Christmas Trees 2004-2005. Michigan Department Of Agriculture, United States Department of Agriculture, National Agricultural Statistics Service, Michigan Field Office. Webpage:
http://www.nass.usda.gov/Statistics_by_State/Michigan/Publications/Michigan_Rotational_Surveys/mi_nurs05/nurs05.pdf
Accessed: 03/09/07.

Anonymous. 2006. Michigan's 2006 Water use conservation plan. Michigan Department of Agriculture. Webpage:
http://www.michigan.gov/documents/mda/MDA_WUR2006Packet_181523_7.pdf
Accessed: 03/09/07.

Anonymous. 2007. Floriculture and Nursery Crops Yearbook. FLO-2007. September. Economic Research Service. USDA.
Website: http://www.ers.usda.gov/Publications/Flo/2007/09Sep/FLO2007.pdf
Accessed: 03/14/2008.

Beeson, Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hort. 22(2):113 – 115.

Still, D.W. and F.T. Davies, Jr. 1993. Water use, water use efficiency and growth analysis of selected woody ornamental species under a non-limiting water regime. Scientia Hort., 53 (1993) 213 – 223.

LITERATURE REVIEW

LITERATURE REVIEW

Introduction

Frequent irrigation applications and runoff quantity and quality have made water use a major issue facing the container nursery industry today. Nurseries commonly group different types of plants together, regardless of water use, and irrigate at a common rate likely applying irrigation amounts in excess of plant needs for some species. These practices have worked in the past because in most areas water has been readily available and inexpensive for nurseries to extract. However, laws now limit water consumption for nursery production in areas of California, Florida, North Carolina, Oregon, and Texas (Beeson et al., 2004). With legislation expected to become more stringent, it is essential that growers find ways to conserve water without detracting from production schedules and crop quality.

Many variables affect the amount of irrigation applied at container nurseries including: type of irrigation system used, application frequency and duration, type of plants grown, and weather variables. This review will cover research on the following topics relevant to water use and conservation at container nurseries.

1. Brief Overview of the Importance of Water to Plants
2. Overview of Container Nursery Irrigation and Runoff
3. Irrigation Methods

    Overhead Irrigation

    Irrigation Efficiencies

Irrigation Uniformity

Microirrigation

4. Irrigation Scheduling

Cyclic Irrigation

Leaching Fraction

Substrate Water Deficit Scheduling

5. Irrigation Scheduling Based on Evapotranspiration

Direct Measurement of Soil Depletion

a. Lysimeter/Balance Approach

b. Tensiometers

c. Soil Measuring Sensors

Energy Balance Approach

Crop Yield and Evapotranspiration Relationships

Water Balance Approach

1. Brief Overview of the Importance of Water to Plants

Water is one of the most common substances on earth and is essential for the existence of life. The importance of water for plant growth and survival has been known by ancient civilizations since the beginning of recorded history. Irrigation systems were in use by 2000 BC in Babylonia (modern Iraq) and China and by at least 5000 BC in Egypt (Hagan et al., 1967; Masse, 1981; and Kramer and Boyer, 1995). However, little research was conducted on plant water relations prior to the 20th century (Kramer and Boyer, 1995). In 1950 the amount of irrigated land worldwide was 95 million ha and this increased dramatically to 250 million ha by 1980 (Stewart and Nielsen, 1990). Since then this increase has slowed primarily because of limited new land area suitable for agriculture.

Water is important to plant life as a constituent, a solvent, a reactant, and for maintaining plant turgor. Results of decreasing water content in plants includes: loss of turgor and wilting, cessation of cell enlargement, closure of stomata, reduction in photosynthesis, and interruption of basic metabolic processes (Kramer and Boyer, 1995). Water is an important component of all plants and comprises greater than 80% to 90% fresh weight of most herbaceous plants and greater than 50% fresh weight of woody plants (Kramer and Boyer, 1995). Water also serves as a solvent for gases, minerals, and other solutes allowing theses substances to enter a plant for use. Once inside the plant water facilitates the movement of these substances from cell to cell and organ to organ (Kramer and Boyle, 1995). Water is also a reactant and is involved in many plant processes. It is the source of hydrogen in carbon fixation and is used with carbon dioxide and sunlight to make sugars (Kramer and Boyer, 1995). Finally, the presence of water in plants maintains plant turgidity, providing structure and support. Plant turgor is also important in cell enlargement, stomatal opening, and movement of plant parts such as leaves and petals (Kramer and Boyer, 1995).

2. Overview of Container Nursery Irrigation and Runoff

One way container-grown crops differ from field crops is that many require daily irrigation during the peak growing season. Container volumes and substrate components limit the amount of water and nutrients available to plant roots for uptake (Dole et al., 1994). Six container nurseries in Alabama were monitored in 1989 and 1990, and growers generally irrigated for 1 h daily during the growing season (Fare et al., 1992). Growers thought they were applying 2.5 $cm \cdot h^{-1}$ with overhead sprinkler applications, but irrigation amounts varied widely depending on nursery ranging from 0.8 cm to 3.2 cm (Fare et al., 1992). Weatherspoon and Harrell (1980) reported that as little as 13% to 26% of irrigation water applied was retained in the container. Irrigation applied that misses the container or that leaches from the container can potentially leave the nursery carrying with it nutrients and other agricultural chemicals that may contaminate nearby water resources. One factor affecting how much runoff will leave a nursery is production surface type. To suppress weed growth, production surfaces are generally covered with a polyethylene or woven polypropylene membrane, many of which are semi-impermeable to impermeable to water infiltration. Rock is another common production site covering, and water flow on rock surfaces can be high leading to large quantities of runoff. Water flowing at fast rates horizontally is prevented from infiltrating the soil where chemicals and fertilizers can be absorbed and degraded before mixing with surface waters (Harris et al., 1997). Harris et al., (1997) reported that 15% to 35% of rainfall and irrigation inputs to nursery production areas were recovered as drainage.

Fertilizers and other agricultural chemicals applied over the production area are carried in runoff and can pose a threat to surrounding water resources.

Contamination by nursery runoff is classified as a non-point source of pollution (Fain et al., 2000). In a four and a half month study on nitrate concentrations from controlled-release fertilizers Yeager and Cashion (1993) reported that nitrate concentration in runoff exceeded the 10 ppm federal drinking water standard set by the U. S. Environmental Protection Agency in 1982. Fare et al. (1994), Jarrell et al. (1983), and Niemiera (1991) reported that nitrate losses through leaching can be 63% when irrigated with 13 mm of water in a single cycle and fertilized with controlled-release fertilizers, 64% under a leaching fraction of 0.4 and a slow-release fertilizer, and 45% when fertilized with a controlled-release fertilizer, respectively. Nitrogen losses from controlled release fertilizers (CRFs) have been reported to range from 12% to 29% (Hershey and Paul, 1982; Rathier and Frink, 1989). Additionally, phosphorous losses from container substrates range from 8% to 27% (Warren et al. 1995). One way to reduce runoff from nurseries is to reduce irrigation inputs. Fare et al. (1994) reported container leachate and total effluent were reduced by approximately 50% and 28% when 8 mm of irrigation was applied compared to 13 mm.

By reducing irrigation inputs container nurseries can also reduce nutrient losses. Karam and Niemiera (1994) reported that leachate volumes under a water application rate (WAR) of 21 $mm \cdot hr^{-1}$ resulted in 66% higher total N (NO_3^--N and NH_4^+-N) leached compared to a WAR of 7 mm/hr. Tyler et al. (1996) reported that a low leaching fraction (LF; quantity of water leached/total water applied) of 0.0 to 0.2 reduced irrigation volume and effluent volume by 44% and 63% compared to a high LF of 0.4 to 0.6, and that after 100 days cumulative losses of NO_3^--N, and P in effluent were 66% and 57% lower from the low LF compared to the high LF. Additionally, Fare et al. (1994) reported total effluent was reduced by 51% with a 6 mm irrigation depth compared to 13 mm. With 13 mm irrigation and a high fertilizer rate, 63% of the total N applied was leached as NO_3^--N, and this amount was reduced by 53% with 6 mm irrigation. Under the low fertilizer rate and 13 mm irrigation as much as 69% of total applied N was leached as NO_3^--N, and this amount was reduced by 64% with the 6 mm irrigation. These studies show that with reduced irrigation applications, nurseries can substantially reduce runoff and nutrient losses. The next challenge is to determine how much irrigation can be reduced without affecting plant growth and quality.

Substantial irrigation reductions with minimum effects on growth have been documented. Welsh et al. (1991) reported that *Photina* × *fraseri* irrigated with 100%, 75%, and 50% replacements of actual water use did not differ in water use, shoot extension, shoot dry weight, leaf number, leaf area, or root area. Tyler et al. (1996) reported that a low leaching fraction (LF) of 0.0 to 0.2 reduced irrigation volume by 44% with a reduction in top dry weight and total plant dry weight of 8% and 10%, compared to a high LF of 0.4 to 0.6 for *Cotoneaster dammeri* 'Skogholm'. Groves et al. (1998) reported similar results that 90% of maximum top growth of *C. dammeri* 'Skogholm' and *Rudbeckia fulgida* 'Goldstrum' occurred with up to a 40% reduction in irrigation volume. In the study by Groves et al. (1998) daily irrigation volume of greater than

900 ml·container^{-1}·d^{-1} was required for maximum growth of both species and reductions in growth of 24% to 35% occurred at irrigation volumes of 200 ml·container^{-1}·d^{-1}.

A successful water conservation plan should not extend the production schedule because producing a marketable sized plant in the shortest time possible is a main objective of nurseries. One way to conserve water and reduce runoff is to apply the minimum amount of water required for optimal plant growth (Yeager et al., 1997). According to current best management practices (BMP's) irrigation applications should replace the amount of water lost since the last irrigation (Yeager et al., 1997). Plant DWU is the combined water loss from plant transpiration and substrate evaporation (Tyler et al., 1996; Yeager, 2003) and is a key component to efficient irrigation scheduling. In order to implement this type of irrigation scheduling the DWU of currently grown species and cultivars must be known or measured. However, scientific information regarding water use requirements of woody ornamentals is limited.

3. Irrigation Methods

Different systems are used for delivering irrigation to container-grown crops. Setup and maintenance cost, container size, plant spacing, labor, and size of operation are factors that determine what method a nursery will use.

Overhead Irrigation

Overhead irrigation systems are most commonly used for container sizes 15 L and under (Beeson and Knox, 1991; Beeson, 1992). Garber et al. (2002) surveyed 102 Georgia container nurseries and reported that nearly all containers smaller than 20 L (#5) were irrigated by overhead systems. Some advantages of overhead systems are the immediate detection of blockages, easy adjustment of the volume of water delivered, frost protection, and overhead chemical application through the irrigation system (Goodwin et al., 2003; Haman and Yeager, 1997).

Irrigation Efficiencies

One way to describe the performance of an irrigation system is irrigation efficiency (IE). Irrigation efficiency is expressed as a percentage, and one calculation of IE is the ratio of the volume of water used by the plants to the volume of water applied, minus a change in storage (Burt et al., 1997).

$$IE = [\text{irrigation volume used} / (\text{volume applied} - \text{change in storage})] \times 100$$

Irrigation efficiency varies among overhead systems depending on container size, operating pressure, nozzle size, wind, container spacing, and plant canopy interactions. Beeson and Knox (1991) reported that the percentage of applied overhead irrigation reaching the substrate varied from 57% to 70% for 3.8 L containers and 30% to 47% for 11.4 L containers depending on plant type, spacing, and sprinkler type. A large part of water use research in the 1990's focused on increasing IE and this interest continues today (Warren and Bilderback, 2005).

Irrigation application efficiency (IAE) is another measurement of irrigation system performance. Irrigation application efficiency is the percentage of applied water that is retained in the rooting volume. Irrigation application efficiency includes irrigation of non-target areas, evaporation during an irrigation event, and container drainage (Beeson and Yeager, 2003). Tyler et al.(1996) described IAE with the following equation:

$$\text{IAE} = [(\text{irrigation volume applied} - \text{volume leached}) \div \text{volume applied}]$$

Beeson and Knox (1991) reported IAEs of 37% for pot-to-pot spacing and 25% for 7.6 cm spacing of three landscape species irrigated with overhead irrigation. They concluded that the low efficiencies were due to container spacing, canopy shedding and retention of water.

One component of IAE is overhead application efficiency (OAE). Overhead application efficiency is the percentage of water applied over the production area occupied by containers that is retained in the substrate and does not include non-target areas outside the irrigation zone (Beeson and Yeager, 2003). Beeson and Yeager (2003) reported a quadratic decline in OAE with increasing spacing of *Viburnum odoratissimum* Ker-Gawl, *Rhododendron spp.* L. 'Southern Charm', and *Ligustrum japonicum* Thumb. in 11.4 L containers.

Evaporation and drift losses from overhead irrigation systems can be substantial and can lower IE. Yazar (1984) reported evaporative losses between 1.5% and 16.8% for overhead systems. Variables such as droplet size, nozzle angle, operating pressure, and weather variables including wind speed, vapor pressure deficit, air temperature, and solar radiation are listed by McLean et al. (2000), as factors contributing to evaporative losses. During hot, dry, and windy periods evaporative losses of 30% from overhead systems have been reported (Spurgeon et al., 1983). Evaporation loss can be reduced by increasing droplet size either by increasing the sprinkler nozzle diameter or by lowering the pressure at which the irrigation is applied. Irrigating when relative humidity is high and air temperature and wind speed are low will also reduce losses from evaporation (Smajstria and Zazueta, 1994). Reducing evaporative losses of overhead irrigation systems can increase IE and help conserve water.

Irrigation Uniformity

Because water applied by overhead irrigation is not 100% uniformly distributed over the production area, irrigation is often applied to adequately water the plant receiving the least amount of water, while other plants receive excess irrigation. As uniformity of a system decreases, the system must run longer, resulting in higher water use and increased runoff. Other problems that may result from low uniformity are water-logging, plant injury, and transportation of chemicals to groundwater (Solomon, 1983). Distribution uniformity (DU) is defined by Burt, et al. (1997) as "a measure of the uniformity with which irrigation water is distributed to different areas in a field". Distribution uniformity is used to report how uniform water is applied through an irrigation system over the irrigated area. Distribution uniformities of 80% and higher are recommended for container-grown plants and indicates that irrigation is being applied evenly to all plants in the irrigation zone (Yeager, 2003). Factors contributing to low uniformity in overhead irrigation systems include: improper pipe diameters and operating pressure, sprinkler heads and nozzles incorrectly matched with operating pressure, inadequate sprinkler overlap, wind, deterioration of system components with time (pump efficiency and nozzle size), and nozzle clogging (Yeager, 2003). Checking uniformity at least once a year and maintaining DU above 80% will minimize runoff resulting from low uniformity in overhead irrigation systems.

Microirrigation

Microirrigation systems such as those using drip and spray stake emitters apply water directly to the container and are practical for larger containers and wider plant spacing. Microirrigation is generally used to irrigate container sizes of 20 L and larger (Beeson and Knox, 1991). In drip irrigation, emitters are placed in containers and water is applied onto a small area of the substrate. In spray stake irrigation the emitter is placed in the container and water is sprayed across the area of the substrate. This type of emitter increases the lateral spread of water, wetting the substrate more thoroughly than drip irrigation (Hoadley and Ingram, 1982). Drip and spray stake systems require a longer time to install and higher maintenance, but generally have higher IEs than overhead systems. However, with decreasing container size and spacing, more emitters are needed, which increases the cost of labor and maintenance. Frequent inspection of microirrigation systems is required to ensure that emitters are not clogged and that filtration systems are clean.

Many studies have been conducted investigating the volume of water applied and runoff of different types of irrigation systems. Goodwin, et al. (2003) reported volumes of water used for overhead, drip, and capillary irrigation systems were 7.13, 2.58, and 3.33 $L\cdot container^{-1}\cdot week^{-1}$ with runoff volumes of 3.00, 0.43, and 0.39 $L\cdot container^{-1}\cdot week^{-1}$. Plants were grown in 2.8 L containers at a density of 11 $containers\cdot m^{-2}$. Weatherspoon and Harrell (1980) compared irrigation systems in two experiments and reported irrigation efficiencies ranging from 13% to 20% and from 44% to 72% for overhead and drip irrigation systems. Despite lower irrigation efficiencies compared to microirrigation, overhead irrigation systems remain popular at container nurseries because of their flexibility, low cost, and low maintenance.

4) Irrigation Scheduling

Irrigation scheduling is the process used to determine how much water to apply and when to apply it (Warren and Bilderback, 2005). Various ways to schedule irrigation applications include: cyclic irrigation, leaching fraction, managed allowable deficit, and scheduling based on evapotranspiration and water use. Irrigation scheduling based on evapotranspiration and water use will be discussed in section five.

Cyclic Irrigation

In cyclic irrigation, the total daily irrigation volume is applied in more than one application with a period of rest between applications. The number of applications used may vary. Cyclic irrigation can be used in overhead and microirrigation systems. Comparing cyclic overhead irrigation to overhead irrigation applied in one cycle, Fare et al. (1994) reported a 34% reduction in water use with cyclic irrigation. Total effluent (runoff and leachate) was reduced by 14% and 10% when applying cyclic overhead irrigation compared with one cycle of overhead irrigation (Fare et al., 1994). The amount of fertilizers leached from containers has also been shown to decrease with cyclic irrigation. Karam et al. (1994) reported 43% higher total N leached from 3.8 L containers irrigated with a single application compared to cyclic irrigation.

Cyclic irrigation conserves water by increasing the water application efficiency (WAE), through the decrease of time-averaged application rate (TAAR) (Warren and Bilderback, 2005), as expressed by the following equation:

$$\text{WAE} = [(\text{water applied} - \text{water leached}) / \text{water applied}] \times 100$$

Time-averaged application rate is comprised of the rate of application, duration of application, and the time interval between applications (Warren and Bilderback, 2005).

Karam and Niemiera (1994) reported a 4% increase in WAE using cyclic irrigation (three applications of 100 ml at 40 min intervals) compared to one continuous application for 3.8 L containers. Lamack and Niemiera (1993) found a linear correlation between increasing WAE (62% to 86%) and decreasing TAAR (7.5 ml min^{-1} to 0.9 ml min^{-1}). In similar work, irrigation applied at the same TAAR in two, four, and six cycles did not increase WAE (Tyler et al., 1996). With a lower TAAR water has more time to thoroughly hydrate the substrate resulting in less leachate. Implementing cyclic irrigation scheduling with lower TAAR into current irrigation delivery systems can increase WAE, thereby conserving water and reducing runoff.

Leaching Fraction

Another method of scheduling irrigation is by using leaching fraction (LF). Leaching fraction is the ratio of water leached to the water applied (Warren and Bilderback, 2005). Leachate carries nutrients from the potting substrate, but also acts to flush soluble salts from the container, preventing accumulation to levels that can damage plants. From a water conservation viewpoint, scheduling irrigation applications with a LF of 0 would be ideal. However, this is difficult to achieve in a production setting because irrigation systems are not 100 percent efficient and some over watering and leaching will occur.

Tyler et al. (1996) used cyclic microirrigation and applied low LF (0.0 to 0.2) and high LF (0.4 to 0.6) irrigation regimes to 3.8 L containers. Decreases in irrigation volume and runoff of 44% and 63% were reported for low LF irrigation compared with high LF irrigation. Under low LF irrigation cumulative NO_3^- - N and NH_4^+-N in runoff were reduced 66% and 62% compared with high LF irrigation (Tyler et al., 1996). Irrigating using low LF can conserve water and help keep nutrients in the substrate by decreasing losses through leaching.

Electrical conductivity (EC) of the substrate needs to be monitored to ensure that soluble salt concentrations remain in the acceptable range for optimum plant growth. The recommended range for container-grown plants fertilized with controlled release fertilizers is 0.2 to 0.5 $dS \cdot m^{-1}$ (Yeager et al., 1997). Ku and Hershey (1991) determined that with overhead irrigation, a low LF increased soluble salt concentrations in the middle and lower third of the container medium. Low LF irrigation schedules may require periodic flushing of soluble salts from containers through a high LF irrigation event. Depending on climate and location, rainfall may be sufficient to leach soluble salts from containers on a periodic basis to help facilitate low LF irrigation scheduling. Scheduling irrigation using low LF may best be suited for more efficient irrigation systems, such as microirrigation, because high IE and uniformity are required to accurately apply the proper volume of water needed to maintain near zero LFs. However, more research is needed to identify the LF that provides optimum growth while conserving the most water.

Managed Allowable Deficit Scheduling

Some irrigation schedules involve initiating an irrigation event when available moisture in the container is depleted below a certain threshold. This method affects IE and irrigation timing. However, container moisture content can only be allowed to decrease so far before water stress and reduced plant growth will result. Another concern is water channeling during irrigation applications if substrates containing pine bark are allowed to reach moisture levels that promote hydrophobic conditions. The hydrophobic properties of pine bark, a component of many soil-less substrates used in nursery production, make evenly rewetting an excessively dried substrate difficult during the next irrigation event (Powell, 1987). Increased channeling results in excess leaching coinciding with a decrease in IE (Beeson and Haydu, 1995; Warren and Bilderback, 2005).

In managed allowable deficit (MAD) irrigation scheduling, the substrate dries to a predetermined level before irrigation is applied. In theory MAD irrigation conserves water through fewer irrigation applications because water is only applied when the moisture deficit reaches the predetermined level. The optimal substrate moisture deficit at which to irrigate will depend on species, plant size, and container substrate used. All these factors must be considered before implementing MAD irrigation to avoid affecting plant growth and excessive substrate drying. Welsh and Zajicek (1993) found a 15% reduction in shoot growth in rooted cuttings of *Photina x fraseri* L. when the substrate was dried to 50% available water prior to irrigation.

Beeson (2006) investigated if using MAD irrigation schedules of 20%, 40%, 60%, 80% deficits of plant available water could conserve water compared with a control of 18 $mm \cdot d^{-1}$ while maintaining acceptable growth rates of 11.4 L container-grown *Viburnum odoratissimum* Ker Gawl, *Ligustrum japonicum* Thunb., and *Rhaphiolepis indica* Lindl. Relationships between cumulative actual evapotranspiration (ET_A) and either shoot dry mass or canopy volume were highly correlated indicating that a minimum amount of cumulative evapotranspiration (ET_A) is needed for plants to reach a certain size. Despite fewer irrigation applications with increasing MAD treatments, irrigation amounts for all but the 80% MAD level exceeded the control for *V. odoratissimum* and *L. japonicum*. All MAD treatment levels except the 60% and 80% of *R. indica* received irrigation in excess of the control during the study. For *L. japonicum*, and *R. indica* final growth index of the control, 20%, and 40% MAD treatments were larger than the 60% and 80% MAD treatments. Beeson (2006) concluded that irrigation schedules such as those using high MAD levels that limit replacement of ET_A will lengthen production times needed to grow marketable sized plants. The additional time required for the plants to reach marketable size would require additional irrigation that could exceed the water applied by a non-limiting irrigation regime, resulting in higher water use during the extended production time. Managed allowable deficit recommendations of 20%, 20%, 25% and 40% for *Viburnum odoratissimum* Ker Gawl, *Ligustrum japonicum* Thumb., *Photina x fraseri* L., and *Rhaphiolepis indica* Lindl. have been made (Beeson, 2006; Welsh and Zajicek, 1993). However, more research is needed to determine optimum MAD levels for specific substrates and species to avoid reductions in growth and possible extended production times.

5) Evapotranspiration

For container-grown plants, evapotranspiration is water lost from the container substrate by evaporation and water lost from the plant by transpiration. Estimates of daily evapotranspiration can be used to schedule irrigation. Environmental factors that influence water demand include: rainfall, light intensity, temperature, relative humidity, and wind speed (Knox, 1989). These factors vary depending on location and time of year. Plant species, size, growth rate, and stage of development influence water demand. Research on modeling plant water requirements has been conducted since the 1940s in agronomic crops such as corn and wheat. This research resulted in the development of an equation for actual evapotranspiration (Thornthwaite, 1944):

$$ET_A = ET_0 \times K_C$$

Where ET_A is actual evapotranspiration of the crop of interest, ET_0 is potential evapotranspiration of a reference crop, and K_C is a crop specific crop coefficient. For container crops calculation of ET_A accounts for the container substrate surface area where water enters the substrate and can be calculated as follows (Schuch and Burger, 1997):

$$ET_A = \text{volume of water use } (cm^3) \text{ / container surface area } (cm^2)$$

In the 1940s the Penman-Monteith equation was developed, and since has become the standard for ET_0 calculation (Monteith, 1964; Penman, 1948). Various modifications of the original equation have been made using meteorological variables such as solar radiation, temperature, relative humidity, and wind speed (Beeson, 2005). The Penman-Monteith method of estimating ET_0 is recommended by the United Nations Food and Agricultural Organization (Allen et al., 1999).

There are four main methods for ET_A measurement: 1. direct measurement of soil water depletion, 2. the energy-balance approach using weather data and crop coefficients, 3. using relationships between crop yield or plant growth and ET_A, and 4) direct measurement using the water-balance approach (Burt et al., 1997). Accurate estimates of ET_A are essential for scheduling irrigation based on plant water demand.

Direct Measurement of Soil Water Depletion

Because of the high cost associated with directly measuring soil moisture depletion, measurements are typically taken at a few sites within a field or container production area throughout the growing season. ET_A values are then extrapolated to the entire field. Potential sources of error vary depending on the method used to measure soil moisture. Data from a few selected sites may be highly variable and sources of variation are often unidentifiable. Non-uniform irrigation applications can lead to water deficits in parts of the field not measured directly. Instruments and sensors used to measure moisture content may be incorrectly calibrated. In microirrigation systems, where only part of the substrate may be wet, a representative spot to measure soil moisture content may be difficult to find (Burt et al., 1997). Methods used to estimate ET_A based on soil water depletion are weighing lysimeters, the gravimetric method, and measuring soil moisture content with sensors (Niu et. al., 2006).

Lysimeter and Balance Approach

According to Burger et al. (1987), ET_A can be obtained by weighing a container with the desired plant 1 h after watering and reweighing 24 h later. The difference in mass equals the amount of water lost through evapotranspiration minus any water lost in drainage, and represents the amount of water to apply during the next irrigation cycle. Using a weighing lysimeter to monitor the weight of a container throughout the day can also be used to calculate ET_A. Although highly accurate, lysimeters and balances can be expensive and difficult to move.

This makes multiple measurements over a large area difficult and limits the practical use of lysimeters and balances in a production setting.

Directly Measuring Soil and Substrate Moisture Content

Another approach to estimating ET_A is by measuring the change in soil moisture content between irrigations. Measuring soil moisture content can help growers determine when to water, how much water to apply, and trends in moisture depletion over time. Soil water content has traditionally been measured using gypsum blocks, neutron probes, tensiometers, or by gravimetric sampling (Adamsen and Hunsaker, 2000).

Gypsum blocks are inexpensive. They work by measuring electrical resistance, but respond slowly to changing soil moisture content, can break down as a result of fertilizers dissolving around the block (Mead, 2000), and often need to be replaced yearly (Muñoz-Carpena et al., 2002). Using neutron probes are time consuming and labor intensive making them impractical for container production where a large number of samples for a variety of plant types and container sizes are required.

A computer-controlled drip irrigation system using tensiometers was developed by Lieth and Burger (1989) to irrigate container-grown chrysanthemums. Reductions in water use ranged from 76% to 92% for irrigation that maintained approximate constant moisture tensions of 1.4, 3.5, 5.5, and 9.6 kPa compared to a control irrigation time of 5 $min \cdot d^{-1}$ (Lieth and Burger, 1989). Kiehl et al. (1992) reported that container-grown chrysanthemums received less than 50% of the water applied by a control irrigation application of 5 $min{\cdot}d^{-1}$ (1.9 to 3.1 $ml{\cdot}sec^{-1}$) when irrigation treatments were initiated above constant tension setpoints of 1, 3, and 5 kPa and one variable tension irrigation schedule that was initiated at 7 kPa and turned off when the tension dropped below 2 kPa. Total dry weights of control plants, the 1 kPa constant tension treatment and the variable tension treatment were higher than the constant tension treatments of 3 and 5 kPa (Kiehl et al., 1992). These studies show that tensiometers can be successfully used to schedule irrigation of container-grown plants. However, maintaining reliable contact between the sensor and the substrate can be difficult when tensiometers are used in substrates with porosities higher than 70% (Cornejo et al., 2005). In addition, tensiometers require regular maintenance, as they must be refilled and recalibrated (Cornejo et al., 2005).

Two modern technologies for measuring volumetric soil moisture content are time-domain-reflectometry (TDR) and frequency-domain-reflectometry (FDR) (Hanson and Peters, 2000). Both technologies are types of dielectric soil moisture sensors. Multiple probes can be connected to dataloggers for automatic data acquisition. The cost of TDR systems typically range from $8000-10,000 and capacitance sensors cost around $500, not including dataloggers (Evett,1999). Many field and laboratory studies have shown that TDR and capacitance sensors accurately measure water content in a variety of soil types (Blonquist et al., 2005; Eller and Denoth, 1996; Hanson and Peters, 2000; Proulx, 2001; Topp and Davis, 1985; and Yoder et al., 1998).

Dielectric soil moisture sensors measure the dielectric constant of the soil. The relationship between the square root of the dielectric constant and volumetric moisture content is well documented (Topp et al., 1980 and Whalley, 1993). The dielectric constant of water is 80, which is greater than that of most soil materials (usually around 3 to 4) and that of air (around 1). Thus, water content is the main factor determining the dielectric constant of the soil and water mixture (Anon., 1999).

In TDR, two to four electrodes are inserted into the soil parallel to each other. An electromagnetic signal is applied to the electrodes, travels down their length, and is reflected back. The travel time of the pulse is related to the dielectric constant of the soil. A calibration equation is used to relate the dielectric constant to volumetric soil moisture content (Hanson and Peters, 2000). Blonquist et al. (2005) reported that for higher frequency systems, which included two TDR systems, accuracy was affected by electrical conductivity and temperature variation and to a lesser extent by dielectric relaxation. Dielectric relaxation refers to the lag time in the dielectric constant of a material in response to a changing electric field.

For FDR, the electrodes of the sensor are inserted into the soil and an electrical pulse at a specific frequency is passed through the electrodes and the surrounding soil matrix. This generates a resonant frequency, which is measured by the sensor that changes as the dielectric constant of the soil changes. A calibration equation is used to convert the dielectric constant of the soil to volumetric soil moisture content (Hanson and Peters, 2000). Blonquist et al. (2005) reported that for lower frequency systems, including one FDR probe, accuracy was affected by electrical conductivity and to a lesser degree by temperature variation and dielectric relaxation.

Many of these probes can be calibrated to a specific soil or substrate type for improved accuracy. For container-grown plants, the change in volumetric moisture content represents the volume of water lost from the container plus that used by the plant since the previous irrigation. When determining irrigation rates to replace evapotranspiration, this equals the volume of water to add during the next irrigation. If the volume of substrate in the container is known, the volume of water to apply during the next cycle can be calculated. Scheduling irrigation based on the change in volumetric moisture content eliminates the complex calculations needed to estimate ET_A using ET_0 and K_C. Doing so would allow growers to determine water use from a single measurable variable, thus eliminating spatial variation from equations that use meteorological data collected from other locations to estimate ET_A. Scheduling irrigation according to change in volumetric moisture content would also eliminate the need to derive K_C values for the numerous species of woody ornamentals currently grown.

Dielectric moisture sensors have successfully been used to monitor substrate moisture levels in containers and lysimeters in a variety of experiments (Niu et al., 2006; Cornejo et al., 2005; Cameron et al., 2004; Garcia y Garcia et al, 2004). An automated irrigation controller designed to maintain container substrate levels near volumetric moisture content set-points was researched by

Nemali and van Iersel (2006). Volumetric moisture content was measured by calibrated dielectric moisture sensors connected to a datalogger. Bedding plants were grown in 17.5 L containers in a 60% peat moss:40% perlite (vol:vol) soil-less substrate. Irrigation was applied when the volumetric moisture content dropped below a specific set-point. The system maintained volumetric soil moisture content at the desired level during the experiment and the daily mean volumetric soil moisture content did not exceed the set-point by more than 0.04 $m^3 \cdot m^{-3}$. In addition, minimal runoff was observed. This type of system may be used as a prototype for future irrigation controllers, but further research is needed on systems using multiple moisture sensors to determine how many probes are needed and how to transmit and process data most efficiently. Such systems can be expensive and require a certain amount of technical knowledge. Similar to MAD irrigation scheduling, this type of system requires research on multiple species of container-grown plants to determine the substrate moisture level to at which optimal plant growth occurs with the least amount of irrigation applied. Dr. John Lea-Cox leads a research program at the University of Maryland that is currently researching wireless automated irrigation systems using moisture sensors and has reported the accuracy of TDR technology in a variety of soil-less substrates that will make automated irrigation systems more accurate for actual production settings (Murray et al., 2004).

Energy Balance Approach Using Crop Coefficients

Using crop coefficients (K_C) to estimate ET_A presents several challenges including: K_C values of a specific crop can vary depending on geographic location; K_C values may have been derived for a different irrigation system or frequency; the published K_C may have been derived for a thoroughly watered crop, but irrigated crops may be stressed; K_C values for a crop of interest may be unavailable; and ET_0 measurements from weather stations at other locations may not be representative of water demand at production areas (Burt et al., 1997).

Using K_C values to schedule irrigation may be better suited for field crops where one species is grown over a large area. Unlike field crops container nurseries grow plants of different types, sizes, and container spacing in a relatively small area. Field crops have a uniform canopy while container-grown plants more closely resemble an isolated stand of vegetation. Isolated stands of vegetation are subjected to greater net radiation and advection, resulting in higher K_C values due to increased ET_0 (Doorenbos and Pruitt, 1975).

Currently, the availability of K_C values for nursery crops is limited; making it difficult for growers to estimate ET_A of the crops they grow (Irmak, 2005). Collecting data for the calculation of crop K_C values can be expensive and time consuming because K_C values are species specific and must be derived for each species grown (Beeson, 2005). Another difficulty in deriving K_C values is the accurate estimation of ET_A at different growth stages for each specific crop (Irmak, 2005). The changing relationship between canopy size and container surface area throughout the growing season requires modifications of the K_C to accurately estimate ET_A.

Despite some of these challenges, K_C values have been derived for some container-grown crops. Crop coefficients and water use for container-grown plants varied depending on developmental stage of the plant, plant spacing, size, sampling date, and location (Niu et al., 2006; Schuch and Burger, 1997). Schuch and Burger (1997) estimated K_C values for 12 species of woody ornamentals and classified them according to water use during a 20 month study at two locations in California. They reported that K_C values of low water users remained relatively unchanged over location and time of year and could be used to schedule irrigation. However in high water use species, K_C values fluctuated seasonally from 1 to 4.7, likely due to differences in plant growth stages at different locations and time of year. Using general K_C values to schedule irrigation for high water users was not recommended because modifications of K_C values based on location, microclimate, and plant growth stage would be required (Schuch and Burger, 1997).

Smajstria and Zazueta (1987) found time of year, irrigation efficiency, fraction of ET_A, and fraction of surface area covered with containers to be very sensitive to irrigation requirements in a numerical simulation model developed for container-grown ornamentals in Florida. The model was also sensitive to geographic location, stressing the importance of locally obtained climatic data for estimating irrigation requirements.

Because measuring ET_A to determine K_C is difficult and time consuming, attempts have been made to estimate K_C values using various climate and growth characteristics (Irmak, 2005) including: crop growth stage (Doorenbos and Kassam, 1979), cumulative ET_0 (Hill et al., 1983), fraction of thermal units (Amos et al., 1989), and leaf area development (Wright, 1982). Irmak (2005) calculated K_C values for *Viburnum odoratissimum*, and found relationships relating K_C values to growth index, weeks after transplant, cumulative ET_0, and fraction of thermal units during two growing seasons ($R^2 \geq 0.93$). Using these variables, which are easier to measure than ET_A, to develop base scales to estimate K_C values provides an alternative method of estimating K_C of container-grown crops. Irmak (2005) reported equations using base scale variables to estimate K_C values were affected by season, primarily due to differences in growth rates. Therefore, separate equations would be needed during summer and fall.

Research by Beeson (2004) on *Ligustrum japonicum* L. showed that calculations of K_C based on ET_A normalized by projected canopy area as a function of percent canopy closure were strongly correlated $R^2 = 0.951$ and has potential for developing models to predict K_C for container-grown woody plants. When tested for functionality the model met the objective of producing 90% marketable sized plants and did so 3 weeks faster than a manually controlled irrigation schedule (Beeson and Brooks, 2008).

Evapotranspiration, Crop Yield, and Plant Growth Relationships

Correlating ET_A and yield has been accomplished for a few crops, but requires extensive research. Potential sources of error include the following: inaccurate yield records and a lack of correlation between ET_A and yield, resulting from plant stress, disease, or fertility problems (Burt et al., 1997). For container-grown plants crop yield is represented by growth variables such as growth rate, canopy volume, canopy surface area, shoot dry mass, or growth index.

Correlations between ET_A and ET_0 of container plants have been documented (Fitzpatrick, 1980, 1983; Knox, 1989; and Roberts and Schnipke, 1987). Beeson (1993) reported correlation of ET_A and ET_0 during the last six months of production for 10.2 L container-grown *Rhododendron* sp. 'Formosa' during three periods: quiescent (days 0 to 59), rapid shoot growth (days 72 to

94), and canopy recovery from a hard freeze (days 140 to 172) with r = 0.7790, 0.4910, and 0.67, respectively. During the 22 day period of rapid shoot growth Beeson (1993) obtained a correlation of r = 0.4910, and attributed the weak correlation to a higher ET_A to ET_0 ratio during the middle of the period than at the beginning and the end. When daily ET_A and ET_0 were summed over a four day period the correlation of the model improved to r = 0.8754. Beeson's (1993) models during each period and when daily ET_A and ET_0 were summed over a four day period were not significantly improved by the addition of canopy characteristics. Beeson (1993) attributed the absence of canopy effect to pruning and a hard freeze.

Knox (1989) reported linear regression equations to predict water use that included ET_0 estimated by the Thornthwaite method and growth index for five container-grown woody landscape plants with R^2 values ranging from 0.26 to 0.81. Linear equations using the variables of pan evaporation and growth index were more highly correlated to water use with R^2 values ranging from 0.78 to 0.88 (Knox, 1989).

Beeson (2006) found cumulative ET_A to be highly correlated with either shoot dry mass or canopy volume for three species of woody ornamentals grown in 11.4 L containers. This research shows promise for using plant growth measurements to predict ET_A of container-grown plants. Container-grown plant yield and ET_A relationships could potentially be used for irrigation scheduling, but more research is needed to establish these relationships for a variety of container-grown plants and validate working models through controlled experiments.

Water Balance Approach

Estimating ET_A with a water balance approach can be used if water inputs and outputs of a container can be accurately measured. If all inputs and outputs are known the difference between them equals ET_A. The major challenge and source of error associated with this method is inaccurate measurement of all water inputs and outputs from a container (Burt et al., 1997).

Estimating ET_A from the balance approach at a container nursery is difficult because the volume of water reaching the container substrate is difficult to measure, especially for overhead systems. Even if the volume of water applied over the production area is known, the amount reaching individual containers will vary depending on plant size and water channeling properties of the canopy. Measuring the volume of leachate draining from individual containers is also a difficult task, and not practical on a large scale in nurseries where many different plants at various production stages are grown.

Improving irrigation system performance and efficiency can help to conserve water, but is only one part to a water conservation plan. To minimize water use nurseries will have to group plants with similar DWU together and schedule irrigation according to DWU. Directly measuring the change in substrate volumetric moisture content between irrigation applications using soil moisture sensors and modeling ET_A using K_C values, ET_0, and growth variables are two methods that have shown promise for container nursery irrigation scheduling.

Literature Cited

Adamsen, F.J. and D.J. Hunnsaker. 2000. Water content determination in saline soils using self-contained TDR and electrical capacitance systems. pp. 351-356. In. R.G. Evans, Benham B.L., and Trooien, T.P. (eds.) National Irrigation Symposium: Proceedings of the 4th Decennial Symposium. Phoenix, Arizona, USA.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1999. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO, Rome.

Amos, B., L.R. Stone, and L.D. Bark. 1989. Fraction of thermal units as the base for an evapotranspiration crop coefficient curve for corn. Agronomy Journal. 81:713 – 717.

Anonymous. 1999. ThetaProbe soil moisture sensor. User Manual ML2-UM-1.21. Delta-T Devices Ltd. Cambridge, England.

Beeson, Jr., R.C. 1992. Restricting overhead irrigation to dawn limits growth in container-grown woody ornamentals. HortScience. 27(9):996 – 999.

Beeson, Jr., R.C. 1993. Relationship of potential evapotranspiration and actual evapotranspiration of *Rhododendrom* sp. 'Formosa'. Proc. Fla. State. Hort. Soc. 106:274 – 276.

Beeson, Jr., R.C. 2004. Modelling actual evapotranspiration of *Ligustrum japonicum* from rooted cuttings to commercially marketable plants in 12 liter black polyethylene containers. IVth IS on Irrigation of Hort. Crops. Acta Hort. 664, ISHS 2004.

Beeson, Jr., R.C. 2005. Modeling irrigation requirements for landscape ornamentals. HortTechnology. 15(1):18 – 22.

Beeson, Jr., R.C. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. J. Amer. Soc. Hort. Sci. 131(1):140 – 148.

Beeson, Jr., R.C. and J. Brooks. 2008. Evaluation of a model based on reference crop evapotranspiration (ET_0) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Proc. Vth IS on Irrigation of Hort. Crops. Acta Hort. 792, ISHS 2008.

Beeson, Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hort. 22(2):113 – 115.

Beeson, Jr., R.C. and J. Haydu. 1995. Cyclic microirrigation in container-grown landscape plants improves plant growth and water conservation. J. Environ. Hort. 13:6 – 11.

Beeson, R.C., Jr. and G.W. Knox. 1991. Analysis of efficiency of overhead irrigation in container production. HortScience 26:848 – 850.

Beeson, R.C., Jr. and T.H. Yeager. 2003. Plant canopy affects sprinkler irrigation application efficiency of container-grown ornamentals. HortScience. 38(7):1373 – 1377.

Blonquist, Jr., J.M., S.B. Jones, and D.A. Robinson. 2005. Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems. Vadose Zone Journal. 4:1059 – 1069.

Burger, D.W., J.S. Hartin, D.R. Hodel, T.A. Lukaszewski, S.A. Tjosvold, and S.A. Wagner. 1987. Water use in California's ornamental nurseries. Calif. Agr. 41:7 – 8.

Burt, C.M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L.A. Hardy, T.A. Hardy, T.A. Howell, Members, ASCE, and D.E. Eisenhauer. 1997. Irrigation performance measures: efficiency and uniformity. Journal of Irrigation and Drainage Engineering. 123(6):423 – 442.

Cameron, R.W.F., S. Wilkinson, W.J. Davies, R.S. Harrison-Murray, D. Dunstan, and C. Burgess. 2004. Regulation of plant growth in container-grown ornamentals through the use of controlled irrigation. Acta Hort. 630:305 – 312.

Cornejo, C., D.Z. Haman, and T.H. Yeager. 2005. Evaluation of soil moisture sensors, and their use to control irrigation systems for containers in the nursery industry. ASAE Meeting Paper No. 054056. St. Joseph, MI: ASAE.

Dole, J.M., J.C. Cole, and von Broembsen, S.L. 1994. Growth of poinsettias, nutrient leaching, and water-use efficiency respond to irrigation methods. HortScience 29(8):858 – 864.

Doorenbos, J., and A.H. Kassam. 1979. Yield response to water FAO Irrigation and Drainage Paper No. 33. Rome, Italy.

Doorenbos, J. and W.O. Pruit. 1975. Guidelines for predicting crop water requirements. FAO Irrigation Drainage Paper 24.

Eller, H., and A. Denoth. 1996. A capacitive soil moisture sensor. J. Hydrology. 185(1/4):137 – 146.

Evett, S.R. 1999. Soil moisture monitoring choices for irrigation management. Techniques for Irrigation Management in the 21st Century: An Irrigation Technical Training Session, 33rd Annual Meeting Texas Council of Chapters Soil & Water Conservation Society, June 15 – 18, Kerrville, Texas.

Fain, G.B., C.H. Gilliam, K.M. Tilt, J.W. Olive, and B. Wallace. 2000. Survey of best management practices in container production nurseries. J. Environ. Hort. 18(3):142 – 144.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1992. Monitoring irrigation at container nurseries. HortTechnology. 2(1):75 – 78.

Fare, D.C., C.H. Gilliam, and G.J. Keever. 1994. Cyclic irrigation reduces container leachate nitrate-nitrogen concentration. HortScience. 29:1514 – 1517.

Fitzpatrick, G. 1980. Water budget determinations for container-grown ornamental plants. Proc. Fla. State Hort. Soc. 93:166 – 168.

Fitzpatrick, G. 1983. Relative water demand in container-grown ornamental plants. HortScience. 18(5):760 – 762.

Garber, M.P., J.M. Ruter, and J.T. Midcap. 2002. Survey of container nursery irrigation practices in Georgia. Proceedings Southern Nursery Assn. Res. Conf. 47:598 – 600.

Garcia y Garcia, A., G. Hoogenboom, and L. Guerra. 2004. Container temperature and moisture for estimating evapotranspiration of nursery crops. ASAE/CSAE Meeting Paper No. 042295. St. Joseph, Mich. ASAE.

Goodwin, P.B., M. Murphy, P. Melville, and W. Yiasoumi. 2003. Efficiency of water and nutrient use in containerized plants irrigated by overhead, drip, or capillary irrigation. Australian Journal of Experimental Agriculture. 43:189 – 194.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998. Irrigation volume, application, and controlled-release fertilizers: I. Effect on plant growth and mineral nutrient content in containerized plant production. J. Environ. Hort. 16(3):176 – 181.

Hagan, R. M., H. R. Haise, and T. W. Edminster. 1967. Irrigation of agricultural lands. Amer. Soc. Agron, Madison, WI.

Haman, D.Z., and T.H. Yeager. 1997. Irrigation system selection for container nurseries. EDIS Document AE263. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage: http://edis.ifas.ufl.edu/AE089 Accessed: 01/23/2008.

Hanson, B.R. and D. Peters. 2000. Soil type affects accuracy of dielectric moisture sensors. California Agriculture. 54(3):43 – 47.

Harris, G.L., R.A. Hodgkinson, M. Scott, D.J. Mason, and T.J. Pepper. 1997. Impact of hardy ornamental nursery stock (HONS) systems on the environment: losses of nutrients and agrochemicals. Agricultural Water Management. 34:95 – 110.

Hershey, D.R. and J.I. Paul. 1982. Leaching-losses of nitrogen from pot chrysanthemums with controlled-release or liquid fertilization. Scientia Hortic. 17:145 – 152.

Hill, R.W., E.L. Johns, and D.K. Frevert. 1983. Comparison of equations used for estimating agricultural crop evapotranspiration with field research. Bureau of Reclamation, U.S. Department of the interior, Eng. and Res. Ctr., Denver, Co.

Hoadley, B. and D.L. Ingram. 1982. Drip irrigation for the woody ornamental nursery. Southern Florist Nurseryman. 95(14):20 – 23.

Irmak, S. 2005. Crop evapotranspiration and crop coefficients of *Viburnum odoratissimum* (Ker.-Gawl). Applied Engineering in Agriculture. 21(3):371 – 381.

Jarrell, W.M., S.J. Whaley, and B. Miraftabi. 1983. Slow-release fertilizer and water management with container-grown *Ligustrum texanum.* Scientia Hortic. 19:177 – 190.

Karam, N.S. and A.X. Niemiera. 1994. Cyclic sprinkler irrigation and pre-irrigation substrate water content affect water and N leaching from containers. J. Environ. Hort. 12(4):198 – 202.

Karam, N.S., A.X. Niemiera, and C.E. Leda. 1994. Cyclic sprinkler irrigation of container substrates affects water distribution and marigold growth. J. Environ. Hort. 12:208 – 211.

Kiehl, P.A., J.H. Lieth, and D.W. Burger. 1992. Growth response of chrysanthemum to various container medium moisture tension levels. J. Amer. Soc. Hort. Sci. 117(2):224 – 229.

Knox, G.W. 1989. Water use and average growth index of five species of container grown woody landscape plants. J. Environ. Hort. 7(4):136 – 139.

Kramer, P. J. and J. S. Boyer. 1995. Water relations of plants and soils. Academic Press, Inc. Book online at: http://dspace.udel.edu:8080/dspace/handle/19716/2830 Accessed: 11/11/2008.

Ku, C.S.M. and D.R. Hershey. 1991. Leachate electrical conductivity and growth of potted poinsettia with leaching fractions of 0 to 0.4. J. Amer. Soc. Hort. Sci. 116:802 – 806.

Lamack, W.F. and A.X. Niemiera. 1993. Application method affects water application efficiency of spray stake-irrigated containers. HortScience. 28:625 – 627.

Lieth, J.H. and D.W. Burger. 1989. Growth of chrysanthemum using an irrigation system controlled by soil moisture tension. J. Amer. Soc. Hort. Sci. 114:387 – 392.

Masse, W. B. 1981. Prehistoric irrigation systems in the Salt River Valley, Arizona. Science 214:408 – 415.

McLean, R.K., R. Ranjan, and G. Klassen. 2000. Spray evaporation losses from sprinkler irrigation systems. Canadian Agricultural Engineering. 42(1):001 – 008.

Mead, R. 2000. Soil Moisture Instrumentation: Sensors & Strategies for the 21st century. Landscape Contractor Magazine. Nov/Dec 2000. Pages 8 – 11.

Monteith, J.L. 1964. Evaporation and Environment. State and movement of water in living organisms. Symp. Soc. Expt. Biol. 19:205 – 234.

Muñoz-Carpena, R., Yuncong-Li, and T. Olczyk. 2002. Alternatives of low cost soil moisture monitoring devices for vegetable production in South Miami-Dade County, ABE 333, EDIS. UF/IFAS. FL.

Murray, J.D., J.D. Lea-Cox, and D.S. Ross. 2002. Time domain reflectometry accurately monitors and controls irrigation water applications in soilless substrates. Acta Hort. 633:75 – 82.

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

Niemiera, A.X. 1991. Nitrogen leaching from osmocote as influenced by irrigation amount. Proc. Southern Nurserymen Assn. Res. Conf. 36:84 – 85.

Niu, G., D.S. Rodriguez, R. Cabrera, C. McKenney, and W. Mackay. 2006. Determining water use and crop coefficients of five woody landscape plants. J. Environ. Hort. 24(3):160 – 165.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Royal Soc. London A. 193:120 – 146.

Powell, D. 1987. Water absorbents vs. wetting agents–What's the difference? American Nurseryman. 165(12):59 – 61.

Proulx, S. 2001. Evaluation of the performance of soil moisture sensors in laboratory-scale lysimeters. The University of Manitoba, Winnipeg, Manitoba, Canada. Master of Science Thesis.

Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container grown juniper and Alberta spruce under different irrigation and N fertilization regimes. J. Environ. Hort. 7:32 – 35.

Roberts, B.R. and V.M. Schnipke. 1987. Water requirements of five container-grown *Acer* species. J. Environ. Hort. 5:173 – 175.

Schuch, U.K., and D.W. Burger. 1997. Water use and crop coefficients of woody ornamentals in containers. J. Amer. Soc. Hort. Sci. 122(5):727 – 734.

Smajstria A.G. and F.S. Zazueta. 1987. Estimating irrigation requirements of sprinkler irrigated container nurseries. Proc. Fla. State Hort. Soc. 100:343 – 348.

Smajstria A.G. and F.S. Zazueta. 1994. Evaporation loss during sprinkler irrigation. EDIS Document BUL290. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage:
http://edis.ifas.ufl.edu/pdffiles/AE/AE04800.pdf
Accessed: 10/14/2007.

Solomon, K.H. 1983. Irrigation uniformity and yield theory. PhD Thesis, Utah State University, Logan, Utah.

Spurgeon, W.E., T.L. Thompson, and J.R. Gilley. 1983. Irrigation management using hourly spray evaporation loss estimates. ASAE Paper No. 83-2591. St. Joseph, MI: ASAE.

Stewart, D. A., and D. R. Nielsen. 1990. Irrigation of Agricultural Crops. Agron. Mon. 30, ASA-CSSA-SSSA, Madison, WI.

Thornthwaite, C.W. 1944. Report of the committee on transpiration and evaporation, 1943 – 44. Trans. Amer. Geophys. Union. 25:683 – 693.

Topp, G.C., and J.L. Davis. 1985. Time-domain-reflectometry (TDR) and its application to irrigation scheduling. In Advances in Irrigation, ed., D. Hillel, 107 – 127. San Diego, Calif.: Academic Press.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content. Water Resour. Res. 16(3):574 – 583.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. J. Environ. Hort. 14:194 – 198.

Warren, S.L. and T.E. Bilderback. 2005. More plant per gallon: Getting more out of your water. HortTechnology. 15(1):14 – 18.

Warren, S.L., T.E. Bilderback, and H.H. Tyler. 1995. Efficacy of three nitrogen and phosphorous sources in container-grown azalea production. J. Environ. Hort. 13:147 – 151.

Weatherspoon, D.M. and C.C. Harrell. 1980. Evaluation of drip irrigation for container production of woody landscape plants. HortScience. 15(4):488 – 489.

Welsh, D.F. and J.M. Zajicek. 1993. A model for irrigation scheduling in container-grown nursery crops utilizing management allowed deficit (MAD). J Environ. Hort. 11:115 – 118

Welsh, D.F., J.M. Zajicek, and C.G. Lyons, Jr. 1991. Effect of seasons and irrigation regimes on plant growth and water-use of container-grown *Photina x fraseri*. J. Environ. Hort. 9(2):79 – 82.

Whalley W.R. 1993. Considerations on the use of time-domain reflectometry for measuring soil water content. J. Soil Sci. 44:1 – 9

Wright, J.L. 1982. New evapotranspiration crop coefficients. J. Irrig. and Drain. Div. ASCE 108(IR2):57 – 74.

Yazar, A. 1984. Evaporation and drift losses from sprinkler irrigation systems under various operating conditions. Agricultural Water Management. 8:439 – 449.

Yeager, T. and G. Cashion. 1993. Controlled-release fertilizers affect nitrate nitrogen runoff from container plants. HortTechnology 3(2):174 – 177.

Yeager, T.H. 2003. Implementation guide for container-grown plant interim Measure. EDIS Document ENH-895. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage: http://edis.ifas.ufl.edu/EP152 Accessed 01/23/2008.

Yeager, T.H., C.H. Gilliam, T.E. Bilderback, D.C. Fare, A.X. Niemiera, and K.M. Tilt. 1997. Best management practices guide for producing container-grown plants. Southern Nur. Assoc., Marietta, GA.

Yoder, R.E., D.L. Johnson, J.B. Wilkerson, and D.C. Yoder. 1998. Soil water sensor performance. Applied engineering in Agriculture 14(2):121 – 133.

CHAPTER ONE

WATER CONSERVATION, GROWTH, AND WATER USE EFFICIENCY OF CONTAINER-GROWN WOODY ORNAMENTALS IRRIGATED BASED ON DAILY WATER USE

WATER CONSERVATION, GROWTH, AND WATER USE EFFICIENCY OF CONTAINER-GROWN WOODY ORNAMENTALS IRRIGATED BASED ON DAILY WATER USE

Abstract

The potential of scheduling irrigation based on plant daily water use (DWU) to conserve water without adversely affecting plant growth compared to a traditional irrigation rate was investigated for 20 commonly grown woody ornamentals. Ten different taxa were grown in 2006 and 2007 in10.2 L (#3) containers. Overhead irrigation was applied in 4 treatments: 1. a control irrigation rate of 19 mm-ha (1.07 $L{\cdot}container^{-1}$) applied per irrigation application; 2. irrigation scheduled to replace 100% DWU per application (100DWU); 3. irrigation alternating every other application with 100% replacement of DWU and 75% DWU (100-75); and 4. irrigation scheduled on a three application cycle replacing 100% DWU followed by two applications of 75% DWU (100-75-75). Irrigation applications were separated by at least 24 hours. Daily water use was calculated by measuring the difference in volumetric moisture content 1 hr and approximately 24 hr following irrigation. Total irrigation applied by the 3 DWU treatments was reduced 25% to 75% compared to the control depending on treatment and species. Final growth index of DWU treatments were greater than or equal to the control for all taxa. *Forsythia* × *intermedia* 'New Hampshire Gold', *Hydrangea arborescens* 'Dardom', *Hydrangea paniculata* 'Unique' , and *Weigela florida* 'Wilma' had higher water use efficiency (WUE) values at lower irrigation treatment volumes with no differences in GI or GI increase, indicating that further

irrigation reductions may be possible without affecting growth. Electrical conductivity of *H. arborescens* 'Dardom', *Spiraea fritschiana* 'Wilma, and *Viburnum* x *burkwoodii* 'Chenaultii' did not accumulate to damaging levels in 2007. Irrigation applied based on DWU treatments saved substantial amounts of water while increasing or not affecting final plant size of all species.

Introduction

Conserving water and reducing the environmental impact of runoff are two important issues presently confronting container nurseries. Current regulations and laws limit water consumption by container nurseries in California, Florida, North Carolina, Oregon, and Texas, and nutrient management laws in Maryland, Delaware, and California limit nutrient concentrations in runoff (Beeson et al., 2004). Nurseries in close proximity to urban areas face increasing competition for ground and surface water resources. In some areas of Florida, permitted water allotments for nurseries have decreased by up to 40% over the past 12 years (Beeson et al., 2004). Given a likely increase in cost and lower water availability, the development of irrigation scheduling practices that conserve water and reduce runoff, without adversely affecting crop quality, will be crucial for container nurseries.

One major cause of runoff is poor irrigation efficiency with only 13% to 26% of overhead applied irrigation retained in the container (Weatherspoon and Harrell, 1980). With low percentages of water retained by the container substrate, large quantities of water can leave the nursery and contaminate surrounding water resources. One way to minimize runoff is to group plants with similar water requirements together and follow current Best Management Practices (BMPs) that state that irrigation volume should be based on the amount of water lost since the last irrigation (Yeager et al, 1997). Applying irrigation based on plant demand or daily water use (DWU) is a key concept in water conserving irrigation scheduling.

Daily water use is the combined loss of water from plant transpiration and substrate evaporation (Tyler et al., 1996; Yeager, 2003). This type of irrigation scheduling requires that the DWU of the plant be known. However, scientific information regarding water use of the thousands of species and cultivars of woody ornamentals currently grown is limited and studies evaluating water use of large numbers of woody ornamentals have not been undertaken. One way to measure DWU of container-grown plants is by using soil moisture sensors (Cornejo et al., 2005; Garcia y Garcia et al., 2004). Quantifying the DWU of a wide range of container-grown woody ornamentals will allow various species and cultivars to be categorized by water use so that those with similar water uses can be grouped together to minimize over-watering and runoff generation.

This experiment investigated whether irrigation scheduling as a percentage of DWU could conserve water without negatively impacting plant growth compared to a traditional irrigation rate of 19 mm-ha·application^{-1} (1.07 L·container^{-1}·application^{-1}). The objectives were to: 1. document the effect of scheduling irrigation according to DWU on water conservation and plant growth; 2. determine DWU and water use efficiency (WUE) of several types of container-grown woody ornamentals and place them into water use groups; and 3. evaluate the effect of irrigation volume on substrate soluble salt levels.

Materials and Methods

Site Specifications

The experiment was conducted at the Michigan State University Horticulture Teaching and Research Center (HTRC), Holt, Michigan. The HTRC is located at latitude 42.67°, longitude -84.48°, and elevation 264 m. Twenty species of container-grown woody ornamentals, 10 different species in 2006 and 2007, were grown on a site developed as an outdoor container nursery facility. The production surface consisted of limestone gravel covering a landscape fabric to suppress weed growth. Rainfall was recorded by a Michigan Automated Weather Network (MAWN) weather station located on-site at the HTRC.

Plant Material and Culture

Plant species and cultivars used in the 2006 and 2007 experiments are shown in Table 1.1. Plants of all species were potted up from 5.7 cm (2.25 in) liners received from a commercial nursery, except *Rosa* 'Winnipeg Parks' which were 10 cm (4 in) liners, into 10.2 L (#3) containers from 6 – 9 Sept. 2005 for plants grown in 2006 and from 3 – 7 Sept. 2006 for plants grown in 2007. Container substrate consisted of 85% pine bark:15% peat moss (vol:vol). All species, except *Thuja plicata* 'Atrovirens' in 2006 and *Thuja occidentalis* 'Techny' in 2007, were pruned to a uniform height on 6 June for the 2006 experiment and on 21 May for the 2007 experiment. Plants grown during the 2006 experiment were fertilized on 5 June 2006 with 26 g·container^{-1} of a 17.0N–3.5P–6.6K controlled-release fertilizer with micronutrients, and plants grown during the 2007 experiment were fertilized on 14 May 2007 with 26 g·container^{-1} of a 19.0N–2.2P–7.5K controlled-release fertilizer with micronutrients (Harrell's Inc., Lakeland, FL). One application of Cygon 2-E Dimethoate [O,O-dimethyl- S-(N-methylcarbamoyl-methyl) phosphorodithioate] systemic insecticide was sprayed on plants at a rate of 1.17 L·ha^{-1} on 24 July 2006 for aphid control.

Experimental Design

The experiment was a completely randomized design with subsamples (individual plants). The control treatment was chosen based on results from a survey of growers in the southeastern United States where the average amount of irrigation applied daily ranged from 8 to 33 mm (Fare et al., 1993). Plants received one of four irrigation treatments: 1. a control irrigation rate of 19mm-ha·application^{-1} (1.07 L·container^{-1}·application^{-1}); 2. irrigation scheduled to replace 100% DWU per application (100DWU); 3. alternating every other application with 100% DWU and 75% DWU (100-75); and 4. a three application cycle with one application of 100% DWU followed by two applications of 75% DWU (100-75-75). Irrigation applications were separated by at least 24 hours. Each irrigation treatment was replicated three times. During the 2006 experiment, treatment irrigation amounts were applied daily from 14 June to 30 Sept. and every other day from 1 Oct. to 13 Oct. 2006. During 2007, treatments were applied daily from 8 June to 13 Oct. 2007.

Table 1.1. Container-grown woody ornamentals grown in the 2006 and 2007 irrigation experiments.

2006
Callicarpa dichotoma (Lour.) K. Koch 'Early Amethyst'
Cornus sericea (Michx. F.) L. 'Farrow'
Deutzia gracilis Sieb. and Zucc. 'Duncan'
Kerria japonica (L.) DC. 'Albiflora'
Symphoricarpos ×doorenbosii Krüssm. 'Kordes'
Syringa ×*hyacinthiflora* (Lemoine) Rehd. 'Asessippi'
Syringa ×*prestoniae* McKelv. 'Donald Wyman'
Thuja plicata D. Don. 'Atrovirens'
Viburnum dentatum L. 'Ralph Senior'
Viburnum opulus L. 'Roseum'
2007
Caryopteris ×*clandonensis* A. Simmonds ex Redh. 'Dark Knight'
Cotinus coggygria Scop. 'Young Lady'
Forsythia ×*intermedia* Zab. 'New Hampshire Gold'
Hydrangea arborescens L. 'Dardom'
Hydrangea paniculata Sieb. 'Unique'
Rosa L. 'Winnipeg Parks'
Spiraea fritschiana Schneid. 'Wilma'
Thuja occidentalis L. 'Techny'
Viburnum ×*burkwoodii* Burkw. and Skipw. 'Chenaultii'
Weigela florida (Bunge.) A. DC. 'Alexandra'

Production areas were 4.9 m × 7.3 m and represented one treatment replicate. There were six plants of each species per treatment replicate. The six plants of the ten species grown during each year were randomly arranged in six rows of ten, spaced 45 cm on center within each treatment replicate. Guard plants of the same age and container size bordered each treatment replicate on all sides to minimize edge effects. Species of guard plants varied, but order and arrangement of guard plants in all treatment replicates was identical.

Daily Water Use

Daily water Use (DWU) was determined using a ThetaProbe Type ML2x soil moisture sensor (Delta-T Devices Ltd., Cambridge, England) connected to a ThetaMeter Hand-Held Readout Unit Type HH1 (Delta-T Devices Ltd.). The four sensing rods of the ThetaProbe are 60 mm long. Substrate volumetric moisture content was measured by inserting the rods perpendicular to the substrate surface. Container height was 245 mm. Volumetric moisture content of the container substrate of plants in control treatment replicates was measured 1 h after irrigation and prior to irrigation the following day. Daily water use was measured during 24 h periods without precipitation. The percent difference in volumetric moisture content was multiplied by the average volume of substrate (9.7 $L\cdot container^{-1}$) to determine the volume of water lost from the container. A substrate specific calibration was conducted to improve the accuracy of the ThetaProbe as outlined in the ThetaProbe Type ML2x user manual (Anonymous, 1999; See Appendix A for more information on the principles of operation and calibration of the ThetaProbe).

Irrigation rate of the overhead system was determined by measuring the depth of water applied from 3 of the 12 irrigation zones (treatment replicates) prior to treatment initiation in 2006 and 2007. Irrigation rate was measured using eight rain gauges randomly placed throughout each of the irrigation zones to collect water for 30 min. The irrigation cycle was repeated with the eight rain gauges randomized again for a total of 16 measurements per irrigation zone. For the 2006 experiment the irrigation application rate was 0.475 $mm \cdot min^{-1}$ and for the 2007 experiment the irrigation application rate was 0.434 $mm \cdot min^{-1}$.

Irrigation Applications

Irrigation applications were scheduled with a Rain Bird ESP-12LX Plus controller (Rain Bird Corporation; Azusa/Glendora, CA). Each treatment replicate was controlled by a 2.54 cm Rain Bird 13DE04K solenoid valve (Rain Bird Corporation). Irrigation was applied through 12 Toro 570 Shrub Spray Sprinklers (The Toro Company; Riverside, CA). Sprinklers were mounted on 1.3 cm diameter risers 66 cm high. Sprinkler layout included two 3.67 m diameter 360 degree emitters, four 3.67 m diameter 90 degree emitters, and six 3.67 m diameter 180 degree emitters per treatment replicate. Emitters were arranged in three rows of four, with four 90 degree emitters on the corners, six 180 degree emitters on the edges, and two 360 degree emitters in the middle of the block.

All irrigation was directed into the block and emitters were spaced 3.67 m apart to improve distribution.

Overhead irrigation was used to irrigate the plant species with the lowest DWU on each measurement day. For species with higher DWUs additional water was applied by hand. Irrigation applications were scheduled to apply the correct volume based on irrigation rate and container surface area assuming 100% canopy penetration. Irrigation was initiated between 0700 HR and 0900 HR.

Data Collection

Plant response to irrigation treatments was evaluated by determining plant growth index, internode length, average leaf area, leachate electrical conductivity (2007 only), leachate pH (2007 only), and foliar nutrient analysis (2007 only). Plant growth index (GI) was calculated every 2 to 4 wk throughout the experiment, and was calculated as [(plant width A + plant width perpendicular to plant width A + plant height) / 3]. Plant height was measured from the container rim, and both plant widths were measured in the same direction on each measurement date.

Internode length was measured for all plants except *S.* × *prestoniae* 'Donald Wyman' and *T. plicata* 'Atrovirens' in 2006 and *T. occidentalis* 'Techny' in 2007. We measured the length of current season's growth on three shoots per plant and counted the number of nodes per shoot. The length of each shoot was divided by the number of nodes per shoot to obtain internode length.

Leaves were collected in late September to early October from all plant species, except *Syringa* × *prestoniae* 'Donald Wyman', and *Thuja plicata* 'Atrovirens' in 2006, and *Thuja occidentalis* 'Techny' in 2007. One leaf was collected from the upper, middle, and lower portions of the canopy from each plant. Leaves from the three plant canopy locations were combined, and average leaf area measured using a LI-COR 3100 Area Meter (LI-COR Biosciences, Lincoln, NE).

Electrical conductivity (EC) of leachate was measured with a Horiba Cardy Twin EC Meter (Spectrum Technologies, Inc., Plainfield, IL) and leachate pH was measured with a Horiba Cardy Twin pH Meter (Spectrum Technologies,) using the PourThru extraction procedure as described by Bilderback (2001). Measurements were made 1 to 2 h following irrigation. During the 2007 experiment, leachate EC and pH were measured once during June, July, August, and September for *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* × *burkwoodii* 'Chenaultii'.

Three leaves per plant of *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* × *burkwoodii* 'Chenaultii' were collected for foliar nutrient analysis on 25 July and 7 Sept. 2007. Samples were stored in a cooler at 3°C until shipment to A & L Great Lakes Laboratories, Inc. (Fort Wayne, IN, USA) for analysis of N, P, K, Ca, Mg, Na, S, Fe, Zn, Mn, B, Cu, and Al. Foliar N was determined according to Association of Official Analytical Chemist (AOAC) methods using the Dumas combustion procedure (AOAC 968.06; Anonymous, 2000) with a LECO FP-428 Nitrogen Analyzer (LECO Corporation, St. Joseph, MI, USA). Mineral digestion was by Open Vessel Microwave digestion (SW846-3050B) and mineral analysis for other elements was determined using inductively coupled argon plasma (ICAP) analysis (AOAC 985.01; Anonymous, 2000) using an ARL Accuris Model (Thermo Optek Corporation, Franklin, Massachusetts, USA).

Statistical Analysis

Growth index, internode length, average leaf area, leachate EC, and leachate pH data were analyzed for each species. Growth index, pH and EC data were analyzed as repeated measures using PROC MIXED procedure of SAS (SAS version 9.1; SAS Institute, Cary, NC). When significant at the 0.05 level treatment means were separated using a t-test in the PDIFF option of the LSMEANS statement and the SLICING option of PROC MIXED ($\alpha = 0.05$) to separate treatment means on each measurement date. Leaf area, internode length, water use data, and estimates of water use efficiency were subjected to ANOVA using PROC GLM procedure of SAS (SAS version 9.1; SAS Institute, Cary, NC) and when significant ($\alpha = 0.05$) means were separated by Tukey's Honest Significance test at the 0.05 level.

Results and Discussion

Water Use 2006

Total irrigation applied to the control treatment during the experiment was 2095 mm (117 L·container^{-1}; Data not shown). There were 110 irrigation applications. Total rainfall during this period was 343 mm and resulted in the addition of 19 L·container^{-1} (Figure 1.1A). Irrigation was not applied when rainfall exceeded 20 mm during a 24 hr period which occurred 6 times during 2006 (Figure 1.1A). Total irrigation applied to the 100DWU, 100-75, 100-75-75 treatments was 28% to 70% less, 37% to 74% less, and 40% to 75% less, respectively, than the control depending on species.

Water use data for *Syringa* ×*prestoniae* 'Donald Wyman' is presented, but all additional data was excluded from analysis because of poor growth and burning of leaf margins in all treatments that resulted in a negative growth index during the season. These effects were possibly due to growth inhibitors applied prior to our receiving the liners. Daily water use was measured eight times during 2006 for all species except *C. sericea* 'Farrow' which was measured 9 times. An additional measurement day was needed for *C. sericea* 'Farrow' a week after day 58 as substrate in all treatments except the control treatment was drying out. This could have been due to a change in growth pattern during this time, and was the only occasion during the 2006 and 2007 experiment when container substrate became noticeably dry. During 2006 DWU slightly increased during the middle part of the experiment with a peak on day 39 (22 July 2006) for the majority of taxa (Figure 1.2). Daily water use of *C. dichotoma* 'Early Amethyst' and *C. sericea* 'Farrow' was generally higher than the other taxa in 2006 with DWU during the middle of the experiment exceeding or approaching the control treatment (Figure 1.2A and B). Daily water use of *C. dichotoma* 'Early Amethyst' more than doubled from day 24 to day 39 then slowly decreased before a large drop during the 2 weeks from day 80 until day 94 (Figure 1.2A).

Daily water use of *C. sericea* 'Farrow' peaked twice during the experiment on days 39 and 65 (Figure 1.2B). *C. dichotoma* 'Early Amethyst' was the only species to have a DWU higher than the control during 2006 (Figure 1.2A). This occurred on days 39, 45, and 58 where DWU was 23, 22, and 20 mm-ha·application^{-1}, respectively. Day 39 was the highest or one of the highest days of water use for all species (Figure 1.2A – J). Lowest DWU was on day 115 for all species except *V. opulus* 'Roseum' which was day 94 (Figure 1.2A – J).

The quantity of water applied by each control application of 19 mm-ha equals 190500 L·ha^{-1}·application^{-1}. Average daily irrigation applied during the 110 applications by the 100DWU, 100-75, and 100-75-75 treatments ranged from 27% – 70%, 37% – 74%, and 40% – 75%, respectively, less than the control depending on species (Figure 1.3). Average irrigation applied by the 100-75 and 100-75-75 treatments was lower than the 100DWU treatment, except for *C. dichotoma* 'Early Amethyst' and *T. plicata* 'Atrovirens' where there was no difference between the 100-75 and 100DWU treatments (Figure 1.3). Average irrigation applied by the 100-75 and 100-75-75 treatments was 12% and 17% lower than the 100DWU treatment.

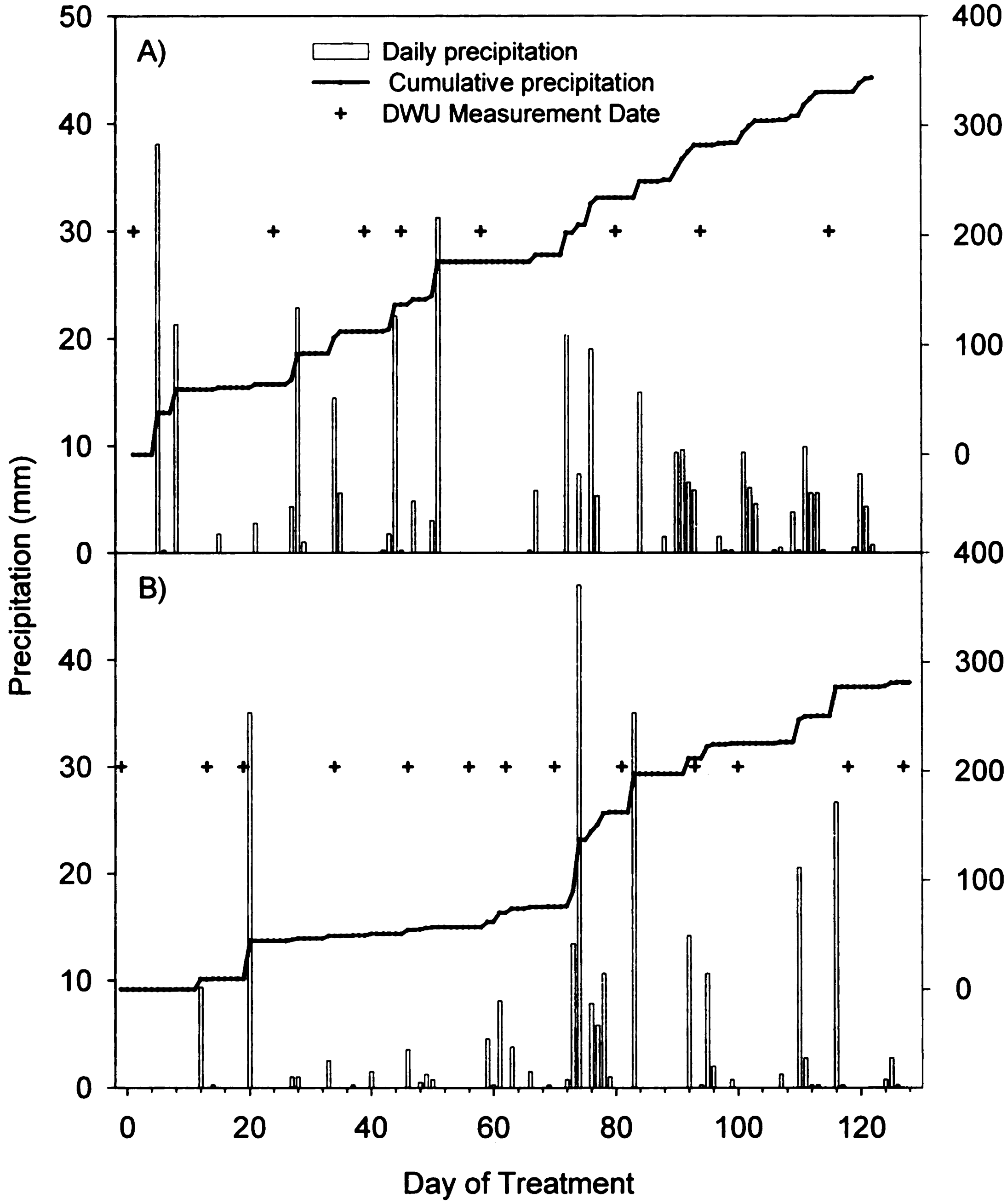

Figure 1.1. Daily (vertical bars) and Cumulative Precipitation (line) from A) 2006 where Day 0 = 13 June and B) 2007 where Day 0 = 7 June. Crosshairs indicate day of daily water use (DWU) measurement. Data taken from a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture and Teaching Research Center. Data courtesy of Michigan State University and the Enviro-weather project.

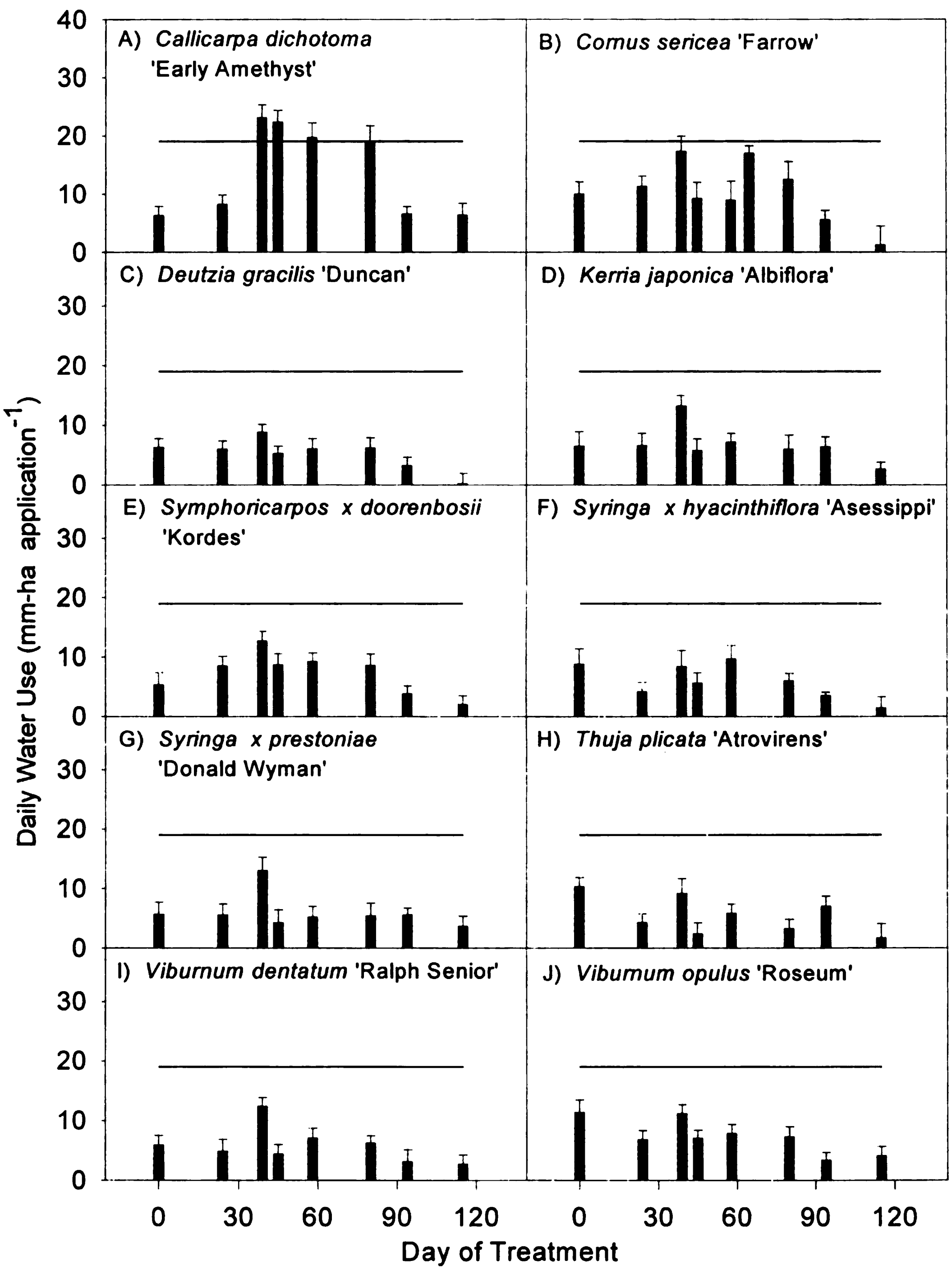

Figure 1.2. Daily water use of ten container-grown woody ornamentals from 13 June to 13 October 2006. Bars show daily water use. Error bars represent standard error of means from 18 plants of each species. Horizontal line shows control treatment of 19 mm-ha. Day 0 = 13 June 2006.

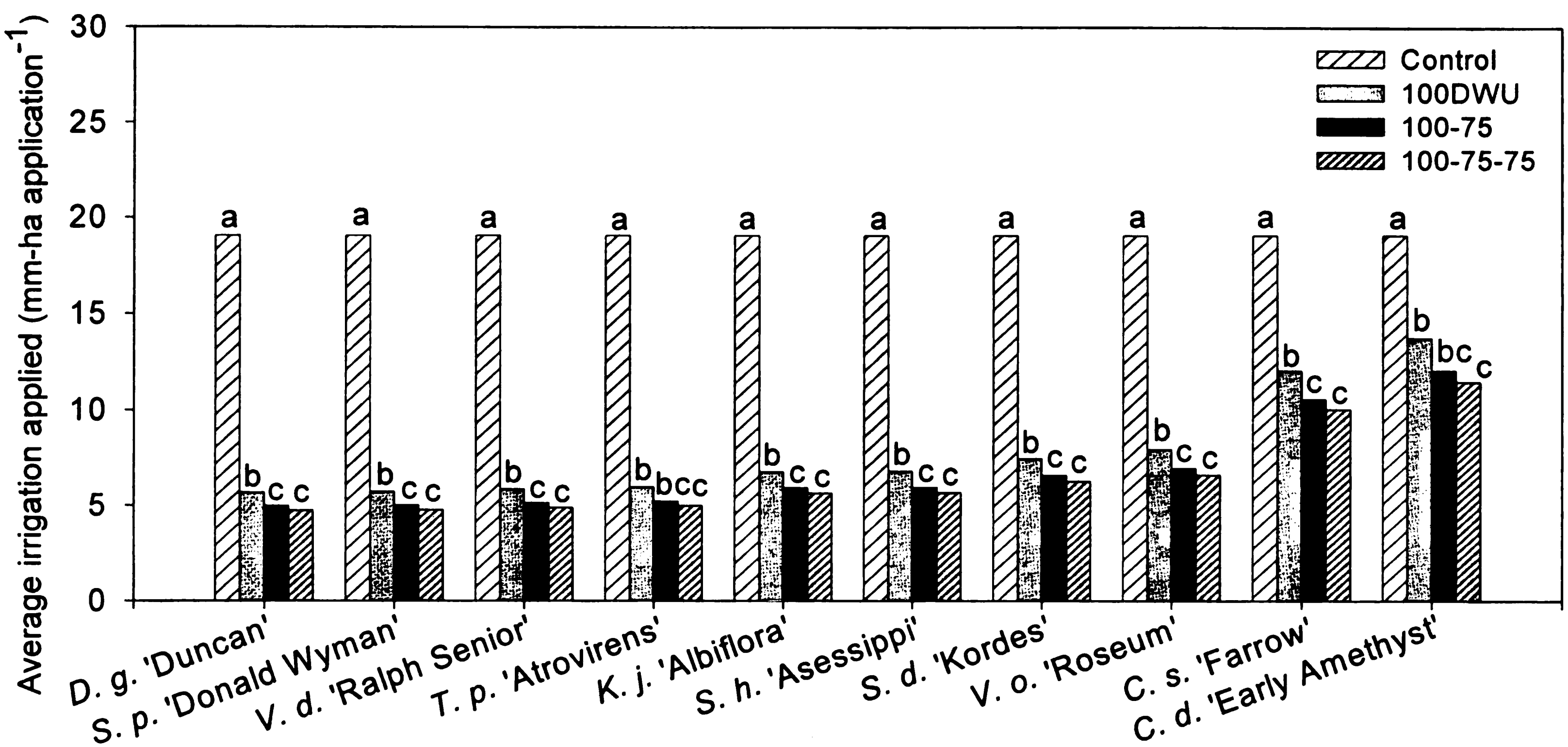

Figure 1.3. Average irrigation depth·application^{-1} applied to 10 species of container-grown woody ornamentals under four irrigation treatments from 14 June through 13 October 2006. Taxa: *Deutzia gracilis* 'Duncan', *Syringa* ×*prestoniae* 'Donald Wyman', *Viburnum dentatum* 'Ralph Senior', *Thuja plicata* 'Atrovirens', *Kerria japonica* 'Albiflora', *Syringa* ×*hyacinthiflora* 'Asessippi', *Symphoricarpos* ×doorenbosii 'Kordes', *Viburnum opulus* 'Roseum', *Cornus sericea* 'Farrow', and *Callicarpa dichotoma* 'Early Amethyst'. Treatments: Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) each application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU. Means separated by Tukey's Test ($\alpha = 0.05$; n = 110).

Water Use 2007

During the 2007 experiment total irrigation applied to plants in the control was 2438 mm (137 L·container^{-1}). There were 128 irrigation applications. Total rainfall during this period was 281 mm and added 16 L·container^{-1} (Figure 1.1B). Irrigation was not applied when rainfall exceeded 20 mm during a 24 hr period which occurred 5 times during the experiment in 2007 (Figure 1.1B). Total irrigation applied to the 100DWU, 100-75, and 100-75-75 treatments was 27% to 68% less, 36% to 72% less, and 39% to 73% less, respectively, than the control depending on species.

Daily water use was measured on 13 days during the 2007 experiment. Daily water use of most taxa gradually increased during the first half of the experiment before gradually declining during the second half (Figure 1.4A – J). Daily water use of most taxa peaked on 2 Aug. 2007 (day 56), which was later in the growing season than the 22 July 2006 peak (day 39; Figure 1.2A – J and Figure 1.4A – J). Daily water use was generally higher for taxa grown in 2007 with 5 taxa having DWU that exceeded the control compared to only one taxa in 2006 (Figure 1.2A and Figure 1.4A, C, E, G, and J). Daily water use exceeded the control for *C. ×clandonensis* 'Dark Knight' on days 13 and 56, *F. ×intermedia* 'New Hampshire Gold' on day 56, *H. paniculata* 'Unique' on days 56 and 62, *S. fritschiana* 'Wilma' on days 46 and 56, and *W. florida* 'Alexandra' on days 56 and 62 (Figure 1.4A, C, E, G, and J). Even though different taxa were grown in 2006 and 2007, overall pattern of DWU was likely affected by precipitation patterns and amounts that led to drier conditions during the first half of the experiment in

2007 (Figure 1.1A and B). Furthermore, nearly steady maximum and minimum daily air temperatures after day 50 during 2007 likely contributed to generally higher average DWU of species in 2007 compared to gradually declining air temperatures after day 50 in 2006 (Figure 1.6A and B). Daily water use on day 56 was highest or one of the highest days of water use for all species in 2007 except *V.* × *burkwoodii* 'Chenaultii' on day 13 (Figure 1.4A – J). Daily water use on day 127 was the lowest or among the lowest days of water use for all species (Figure 1.4A – J).

Average daily irrigation applied by the 128 applications by the 100DWU, 100-75, and 100-75-75 treatments ranged from 27% – 68%, 36% – 72%, and 39% – 73%, respectively, less than the control depending on species (Figure 1.5). These results were nearly identical to those in 2006 (Figure 1.3). Average irrigation applied by the 100-75 and 100-75-75 treatments was lower than the 100DWU treatment for all species, except *V.* × *burkwoodii* 'Chenaultii' where there was no difference between the 100-75 and 100DWU treatments (Figure 1.5). Average irrigation applied by the 100-75 and 100-75-75 treatments was 12% and 17% lower than the 100DWU treatment, the same as in 2006.

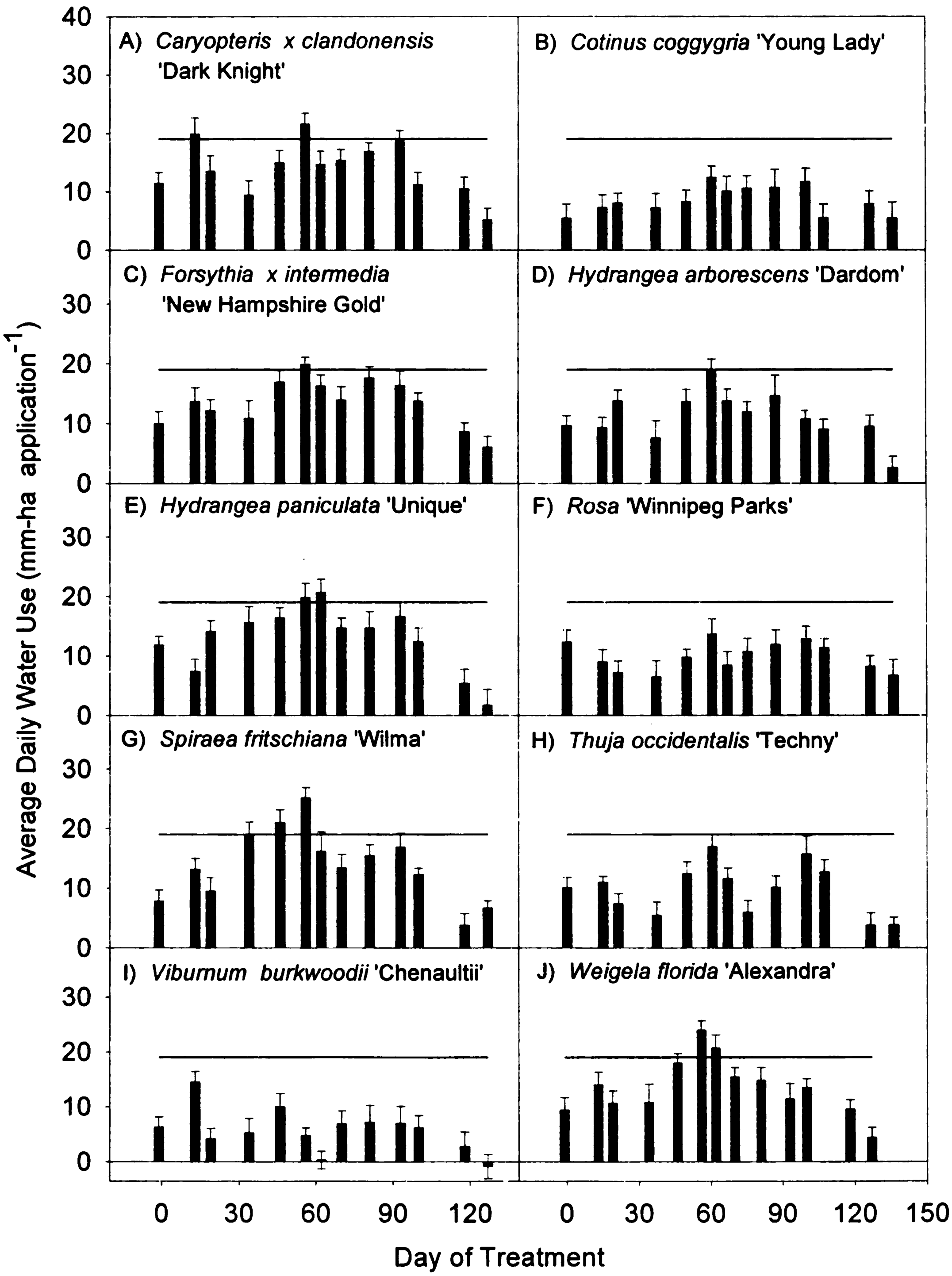

Figure 1.4. Daily water use of ten container-grown woody ornamentals from 7 June to 13 October 2007. Bars show daily water use. Error bars represent standard error of means from 18 plants of each species. Horizontal line shows control treatment of 19 mm-ha. Day 0 = 7 June 2007

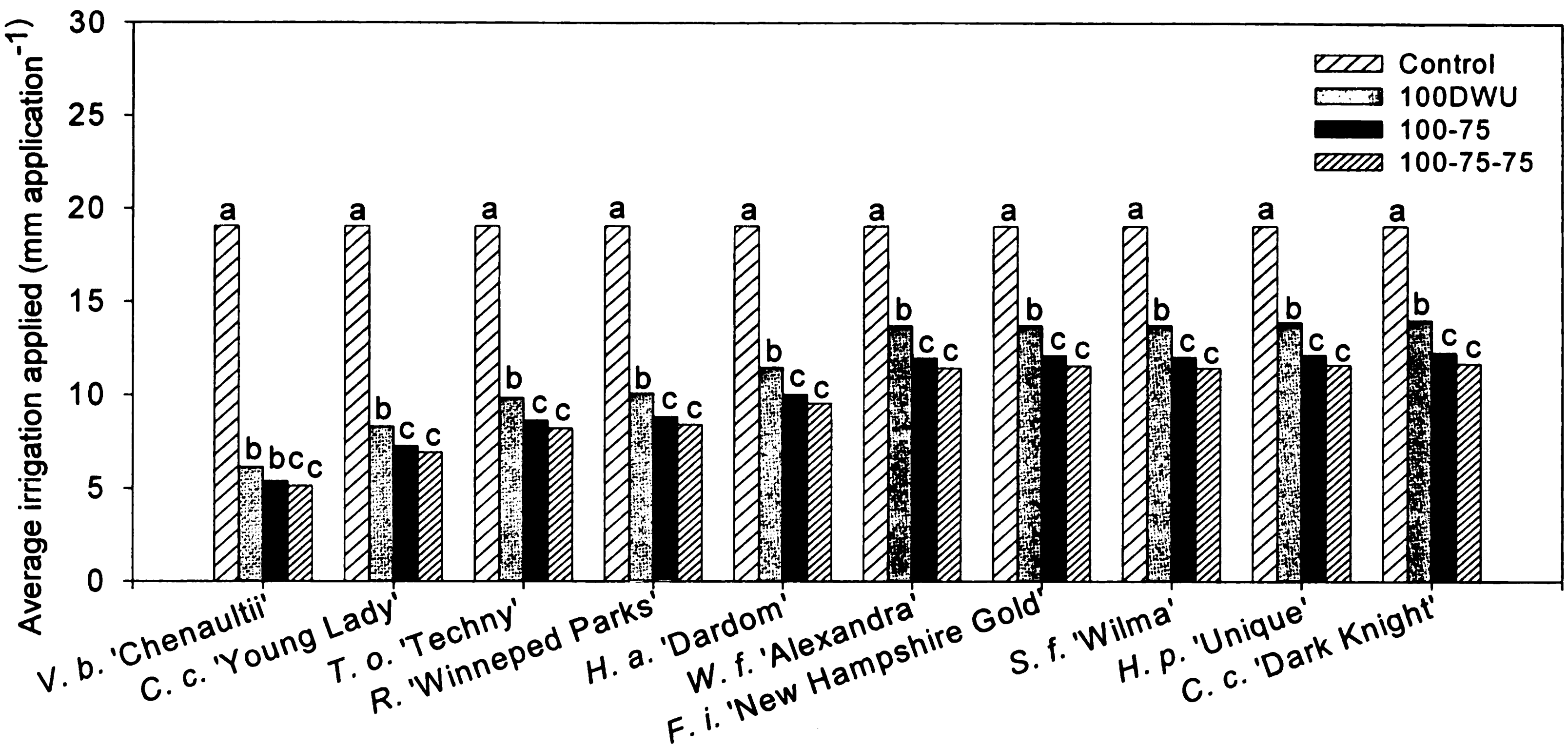

Figure 1.5. Average irrigation depth·application^{-1} applied to 10 species of container-grown woody ornamentals under four irrigation treatments from 8 June through 13 October 2007. Taxa: *Viburnum* × *burkwoodii* 'Chenaultii', *Cotinus coggygria* 'Young Lady', *Thuja occidentalis* 'Techny', *Rosa* 'Winnipeg Parks', *Hydrangea arborescens* 'Dardom', *Weigela florida* 'Alexandra', *Forsythia* × *intermedia* 'New Hampshire Gold', *Spiraea fritschiana* 'Wilma', *Hydrangea paniculata* 'Unique', and *Caryopteris* × *clandonensis* 'Dark Knight'. Treatments: Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) each application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU. Means separated by Tukey's Test (α = 0.05; n = 128).

Still and Davies (1993) classified container-grown woody ornamentals as heavy, moderate, or light water users based on total water consumption. Species in the current study were classified considering average DWU and total water used. Water use classifications were determined for species grown in 2006 and 2007 separately. Experiment duration during 2006 and 2007 was 122 and 128 days and cumulative ET_0 during the 2006 and 2007 experiments was 393.74 mm and 490.10 mm. Daily vapor pressure deficit, reference potential evapotranspiration, and daily total solar flux density for the 2006 and 2007 experiments are shown in figures 1.7A and B, 1.8A and B, and 1.9A and B, respectively. Environmental conditions in 2007 were more stressful than in 2006, and would be expected to affect water use and potentially water use classification.

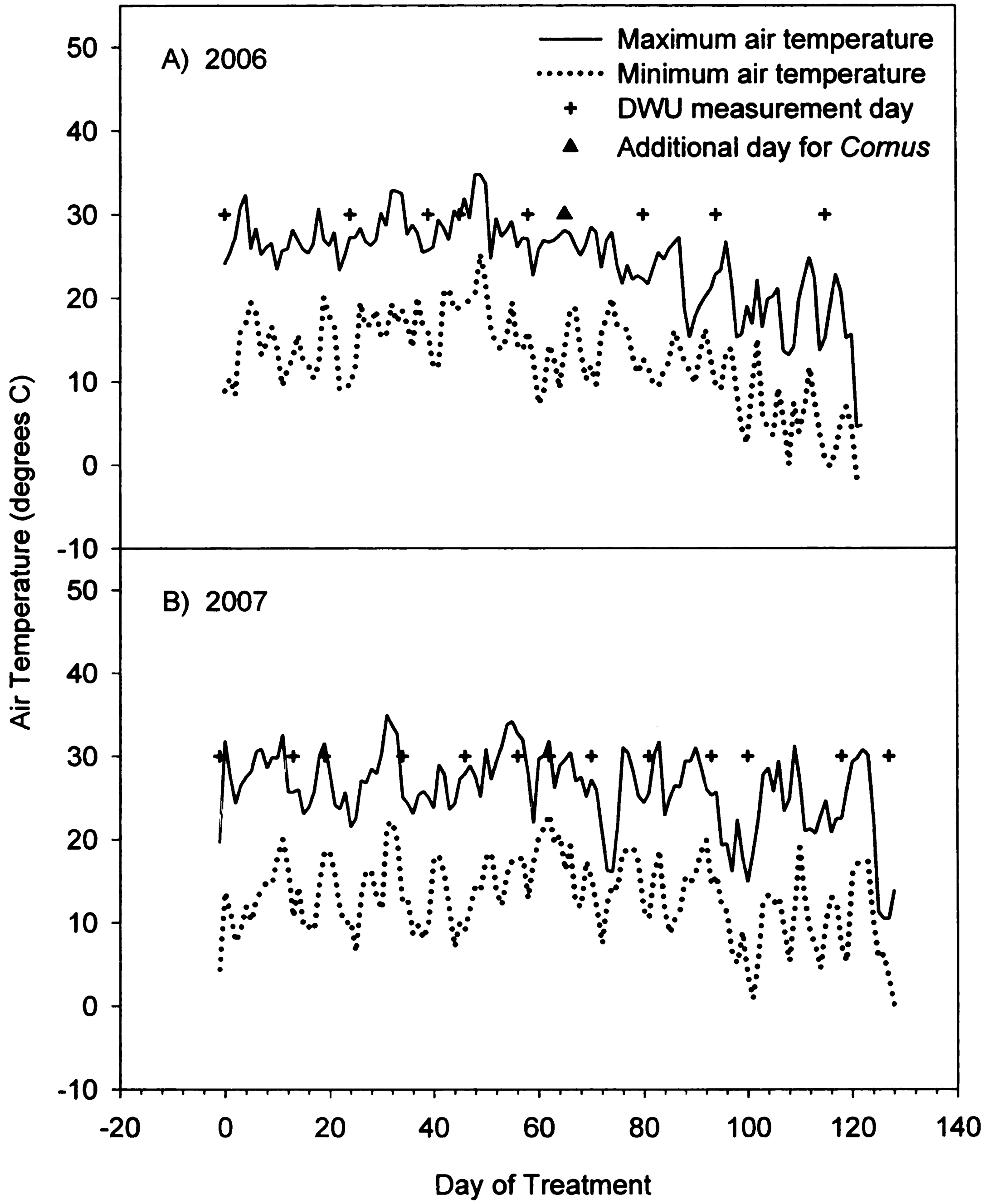

Figure 1.6. Maximum and minimum daily air temperatures from A) 13 June (Day 0) to 13 October 2006 and B) 7 June (Day 0) to 13 October 2007. Air temperatures measured at the 1.5 m level at a Michigan Automated Weather Network (MAWN) weather station located on site at the Michigan State University Horticulture and Teaching Research Center. Data courtesy of Michigan State University and the Enviro-weather project. DWU = daily water use.

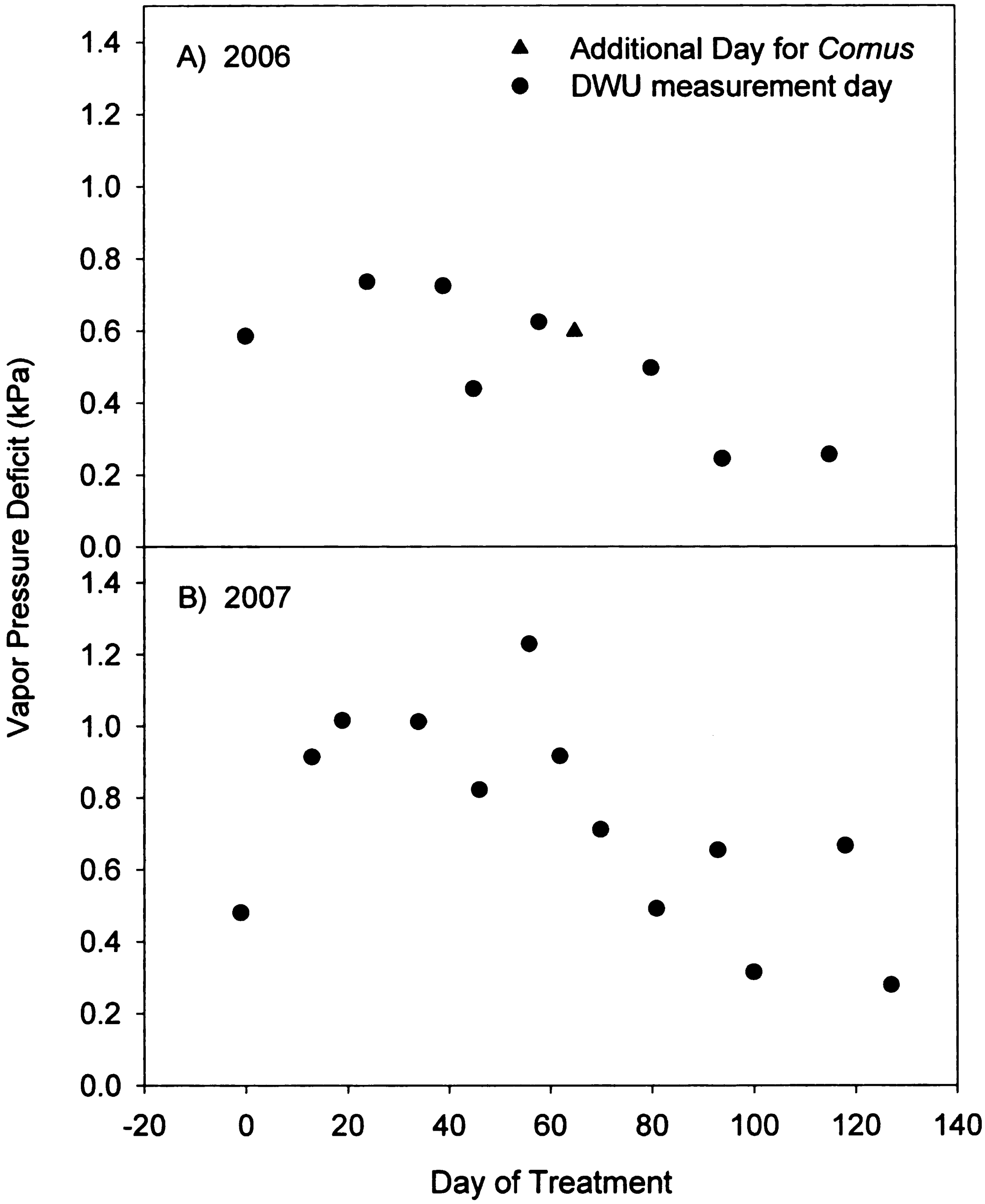

Figure 1.7. Mean daily vapor pressure deficit on days of daily water use (DWU) measurement during A) 2006 and B) 2007. 2006 Day 0 = 13 June and Day 0 in 2007 corresponds to 7 June. Vapor pressure deficit was calculated from data recorded by a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture and Teaching and Research Center. Data courtesy of Michigan State University and the Enviro-weather project. DWU = daily water use.

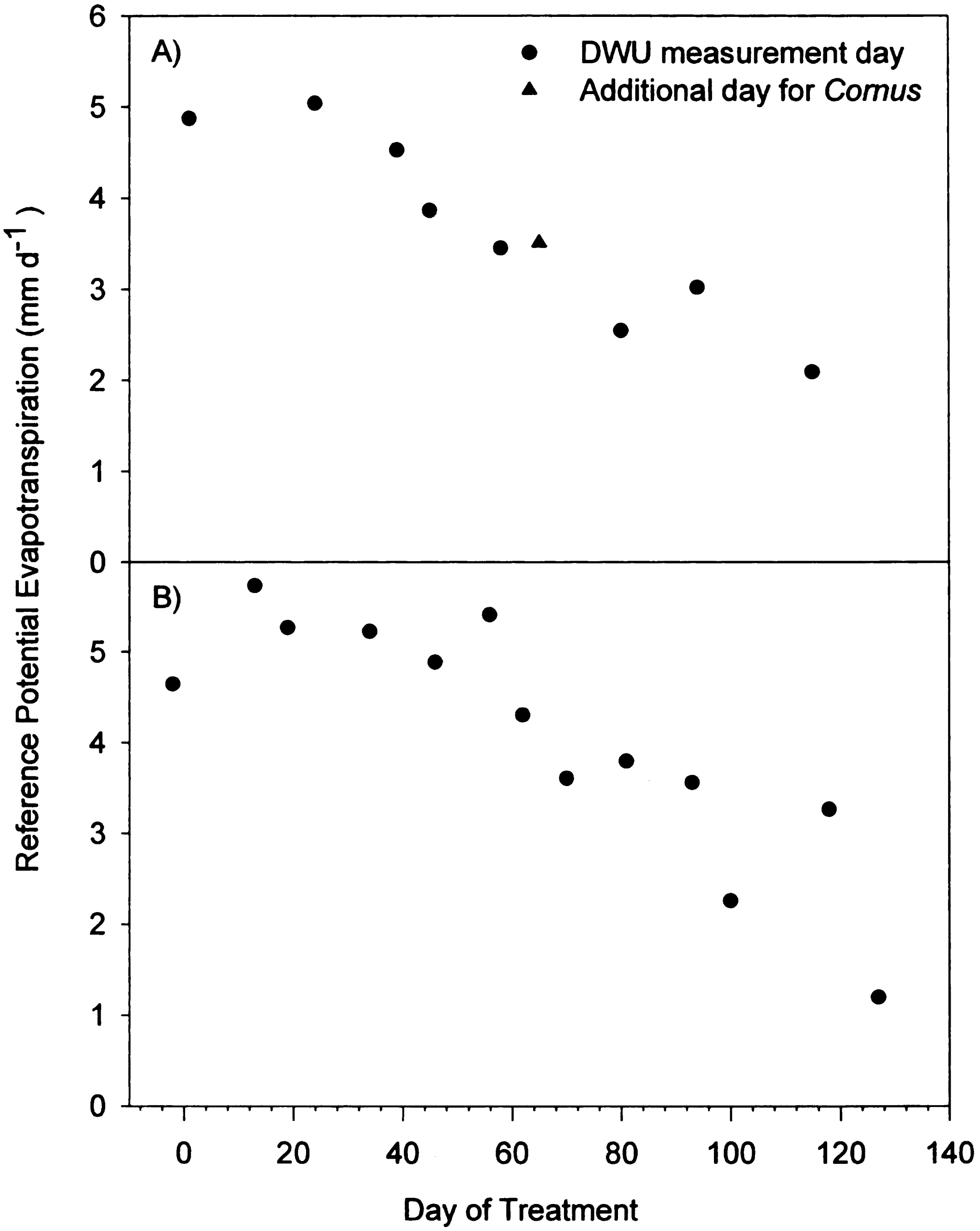

Figure 1.8. Daily Reference Potential Evapotranspiration (ET_P) on days of measured plant daily water use (DWU) during A) 2006 and B) 2007. Day 0 = 13 June 2006 and day 0 = 7 June 2007. ET_P estimated with the modified Penman method according to Kincaid and Heerman (1974). Data from a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture and Teaching Research Center. Data courtesy of Michigan State University and the Enviro-weather project.

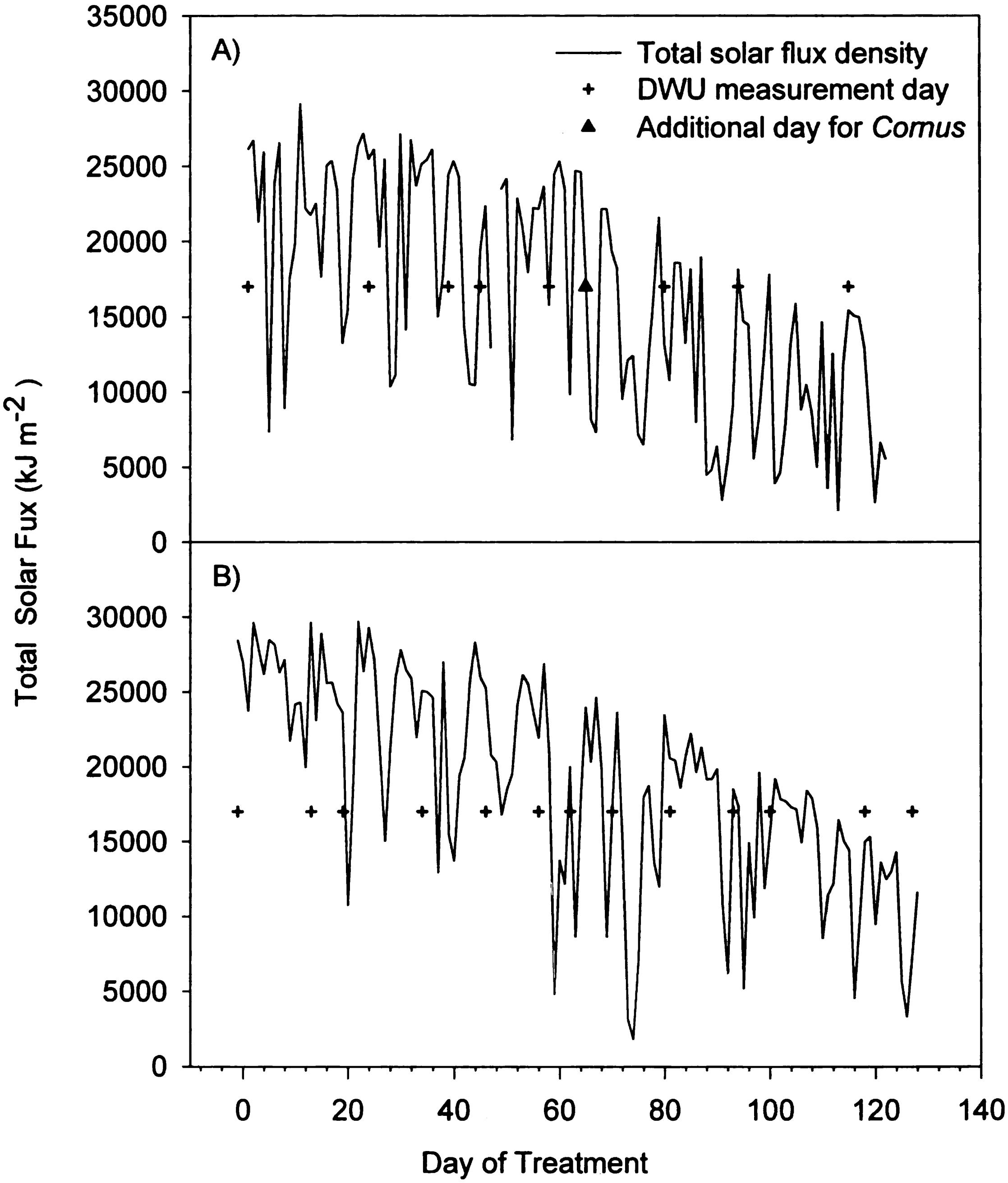

Figure 1.9. Daily total solar flux density (kJ·m^{-2}) from A) 13 June (Day 0) to 13 October 2006 and B) 7 June (Day 0) to 13 October 2007. Data recorded at a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture Teaching and Research Center. Data courtesy of Michigan State University and the Enviro-weather project. DWU = daily water use.

The 9 species in 2006 and the 10 species in 2007 were arranged according to total irrigation applied and assigned to a water use category considering both average DWU and total irrigation applied (Table 1.2). In 2006, *C. dichotoma* 'Early Amethyst' was the only high water user with average DWU of 0.73 L·container^{-1}·application^{-1} (Table 1.2). *C. sericea* 'Farrow' was the only moderate water user in 2006 with average DWU of 0.63 L·container^{-1}·application^{-1} (Table 1.2). The remaining 7 species were low water users with DWU ranging from 0.30 to 0.42 L·container^{-1}·application^{-1}. In 2007 high water users were *C. ×clandonensis* 'Dark Knight', *H. paniculata* 'Unique', *S. fritschiana* 'Wilma', *F. ×intermedia* 'New Hampshire Gold', and *W. florida* 'Alexandra with average DWU values ranging from 0.77 to 0.78 L·container^{-1}·application^{-1} (Table 1.2). Moderate water users were *H. arborescens* 'Dardom', *Rosa* 'Winnipeg Parks', and *T. occidentalis* 'Techny' with average DWU values ranging from 0.55 to 0.64 L·container^{-1}·application^{-1} and total water use of 82 to 71 L·container^{-1} (Table 1.2). *V. ×burkwoodii* 'Chenaultii' was the only low water user in 2007 with average DWU of 0.34 L·container^{-1}·application^{-1} (Table 1.2).

During 2006, seven of the nine species were low water users while in 2007, only one of the ten species was a low water user and five were high water users. Daily reference potential evapotranspiration on DWU measurement days in 2006 averaged 3.7 mm compared to 4.1 mm in 2007. Although species grown in 2006 and 2007 were different, the pattern of higher evaporative demand during

2007 helps explain why a greater number of species were high and moderate water users in 2007 compared to 2006 (Figure 1.8).

Although the low water use group encompassed a wide range of average DWU and total water uses there were no distinct gaps between species to further subdivide the class. This suggests that in some cases the types of plants with which a particular species are to be grouped may be more important than which water use group it belongs. For example, if faced with the option of grouping the low water user *C. coggygria* 'Young Lady' with another low water user *V.* × *burkwoodii* 'Chenaultii' or the moderate water user *T. occidentalis* 'Techny', one may choose to group *C. coggygria* 'Young Lady' with *T. occidentalis* 'Techny' because of closer average DWU and total water used, despite the difference in water use group classification (Table 1.2). One of the main objectives in nursery water conservation is to group species with similar water uses together, and in the example above knowing only the general water use classification of different species would not provide enough information for this purpose. A possible solution would be to report average daily water use of each species along with general water use classifications. Doing so would provide growers with more information with which to base plant grouping decisions regarding species with the closest water requirements even though this may occasionally include species from different water use classifications.

Table 1.2. Water use classifications (H = High, M = Moderate, and L = Low) of 19 container-grown woody ornamentals. Classifications based on average daily water use ($L \cdot container^{-1} \cdot application^{-1}$) and total irrigation applied ($L \cdot container^{-1}$) during the experiment. 2006: 14 June to 13 Oct. 2007: 8 June to 13 Oct.

Species	Avg. Daily Water use (L)	Total Water Used (L)	Water Use Class
2006			
Callicarpa dichotoma 'Early Amethyst'	0.73 ± 0.035[z]	85	H
Cornus sericea 'Farrow'	0.63 ± 0.021	74	M
Viburnum opulus 'Roseum'	0.42 ± 0.014	49	L
Symphoricarpos x *doorenbosii* 'Kordes'	0.40 ± 0.014	46	L
Kerria japonica 'Albiflora'	0.37 ± 0.009	42	L
Syringa x *hyacinthiflora* 'Asessippi'	0.36 ± 0.013	42	L
Thuja plicata 'Atrovirens'	0.33 ± 0.014	37	L
Viburnum dentatum 'Ralph Senior'	0.31 ± 0.011	36	L
Deutzia gracilis 'Duncan'	0.30 ± 0.009	35	L
2007			
Caryopteris x *clandonensis* 'Dark Knight'	0.78 ± 0.017	100	H
Hydrangea paniculata 'Unique'	0.78 ± 0.019	100	H
Spiraea fritschiana 'Wilma'	0.77 ± 0.026	98	H
Forsythia x *intermedia* 'New Hampshire Gold'	0.77 ± 0.015	98	H
Weigela florida 'Alexandra'	0.77 ± 0.019	98	H
Hydrangea arborescens 'Dardom'	0.64 ± 0.014	82	M
Rosa 'Winnipeg Parks'	0.57 ± 0.011	72	M
Thuja occidentalis 'Techny'	0.55 ± 0.018	71	M
Cotinus coggygria 'Young Lady'	0.46 ± 0.011	60	L
Viburnum x *burkwoodii* 'Chenaultii'	0.34 ± 0.015	44	L

[z] Standard error of the mean daily water use of 122 applications in 2006 and 128 in 2007.

Classifying plants into water use groups in this study was partially subjective as exact specifications that determine whether a species is a low, moderate, or high water user have yet to be formally defined. Furthermore, establishing what average DWU and total irrigation applied ranges should comprise a given water use group was not apparent because there were no clear cut-off-points between species. A good example is the wide distribution of average DWU values among low water users in this study, which only evaluated 19 of the thousands of species and cultivars currently being grown. However, the water use values that define a particular water use group should become clearer as water requirements of more species are determined. As a result the ranges of DWU and total irrigation applied that make up a given water use group in this study may need to be adjusted, expanded, or divided into additional water use classifications, i.e. moderate to low. Furthermore, the water use classification of a particular species may change during the growing season due to changes in the growth stage of the plant, changes in environmental conditions that affect DWU. For example, daily DWU of *C. dichotoma* 'Early Amethyst' at 1 day after treatment initiation was 0.35 $L \cdot container^{-1} \cdot application^{-1}$, but on day 39 was 1.29 $L \cdot container^{-1} \cdot application^{-1}$ (Figure 1.2A). As a result seasonal water use classification may also be required.

Growth Index: 2006

There was no effect of irrigation treatment on final growth index (GI) for 6 of the 9 species in 2006 (Table 1.3). The decrease in GI between the last two measurement days for *C. dichotoma* 'Early Amethyst' and *D. gracilis* 'Duncan' was a result of leaf senescence (Figure 1.10 A and B). For *C. dichotoma* 'Early Amethyst' GI of the control was lowest among treatments on days 59, 100, and 127 (Figure 1.10). Lower GI of plants in the control treatment from day 59 to the end of the experiment likely resulted from over-watering during the early and latter parts of the growing season and under-watering during the middle part of the season when DWU of *C. dichotoma* 'Early Amethyst' was higher than the irrigation volume applied by the control (Figure 1.3A). For *D. gracilis* 'Duncan' GI of the 100DWU and 100-75-75 treatments were greater than the control on days 59, 99, and 127 (Figure 1.10B). Differences in GI among treatments of *T. plicata* 'Atrovirens' did not occur until day 105, and GI of the control was lowest among treatments (Figure 1.10C).

Growth Index: 2007

Irrigation volume did not affect GI of 7 of the 10 species in 2007 (Table 1.4). For *C. ×clandonensis* 'Dark Knight', GI of the 100-75 treatment was greater than the 100-75-75 treatment on day 67 with no other differences (Figure 1.11A). Differences in GI among treatments of the *C. coggygria* 'Young Lady' occurred on the last three days of measurement with GI of the control lowest among treatments on day 123 (Figure 1.11B). For *V. ×burkwoodii* 'Chenaultii' GI of the 100DWU treatment was greater than the 100-75 and control treatments on day 99, with no other differences (Figure 1.11C).

Table 1.3. Final growth index (cm) of nine container-grown woody ornamentals under four irrigation treatments in mid-October 2006.

Species	Treatment			
	Control[z]	100DWU	100-75	100-75-75
Callicarpa dichotoma 'Early Amethyst'	69.5[y] b[x]	82.3 a	77.9 a	78.7 a
Cornus sericea 'Farrow'	42.9 a	55.1 a	53.1 a	57.4 a
Deutzia gracilis 'Duncan'	34.7 c	39.7 a	36.2 bc	37.5 ab
Kerria japonica 'Albiflora'	55.7 a	67.9 a	58.5 a	66.0 a
Symphoricarpos x doorenbosii 'Kordes'	49.0 a	44.0 a	48.7 a	47.0 a
Syringa x hyacinthiflora 'Asessippi'	34.8 a	41.6 a	35.3 a	41.6 a
Thuja plicata 'Atrovirens'	32.3 c	38.7 a	35.1 bc	37.0 ab
Viburnum dentatum 'Ralph Senior'	28.5 a	34.1 a	32.9 a	32.9 a
Viburnum opulus 'Roseum'	31.7 a	32.6 a	34.6 a	33.9 a

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Growth index = [(plant width + plant width perpendicular to first plant width + plant height) / 3]

[x]Means within the same row for each species with the same letters are not significantly different from each other. Mean separated by t-test ($p = 0.05$). n = 18.

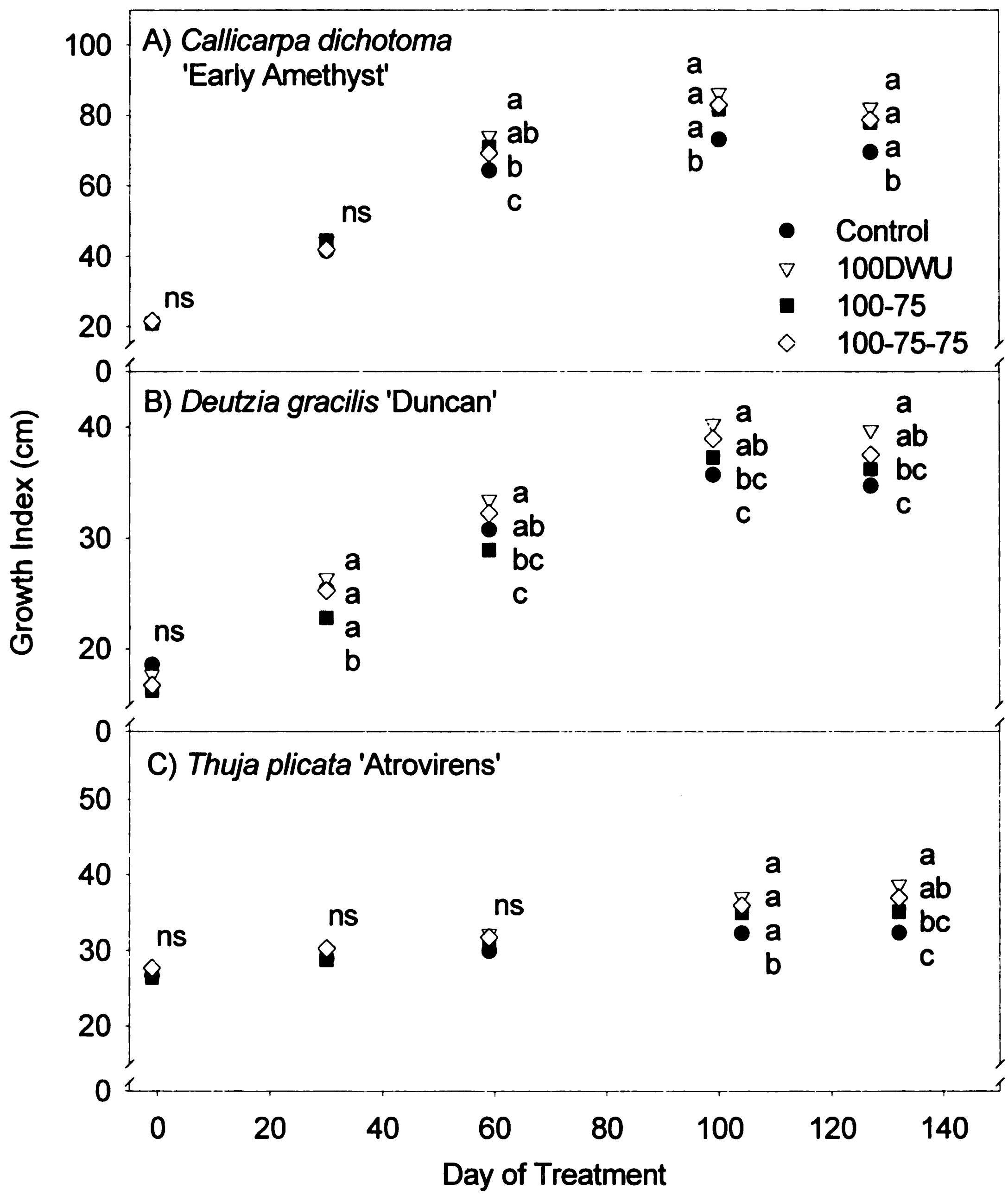

Figure 1.10. Growth index of 3 container-grown woody ornamentals under four irrigation treatments applied from 14 June to 13 October, 2006. Note different y-axis scales. Day 0 = 13 June. Within each day treatment means followed by the same letter are not significantly different (t-test, α = 0.05). ns = not significant. n = 18.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

Table 1.4. Final growth index (cm) of ten container-grown woody ornamentals under four irrigation treatments in mid-October 2007.

Species	Treatment			
	Control[z]	100DWU	100-75	100-75-75
Caryopteris x *clandonensis* 'Dark Knight'	54.9[y] a[x]	54.9 a	56.6 a	52.9 a
Cotinus coggygria 'Young Lady'	28.2 b	34.4 a	32.5 a	32.2 a
Forsythia x *intermedia* 'New Hampshire Gold'	79.8 a	78.7 a	85.9 a	80.7 a
Hydrangea arborescens 'Dardom'	51.3 a	52.3 a	53.9 a	52.6 a
Hydrangea paniculata 'Unique'	59.7 a	63.0 a	67.1 a	61.5 a
Rosa 'Winnipeg Parks'	43.0 a	46.6 a	44.4 a	42.8 a
Spiraea fritschiana 'Wilma'	47.6 a	49.2 a	48.3 a	50.6 a
Thuja occidentalis 'Techny'	38.2 a	39.3 a	42.0 a	37.7 a
Viburnum x *burkwoodii* 'Chenaultii'	19.7 a	24.5 a	20.3 a	22.7 a
Weigela florida 'Alexandra'	55.0 a	56.7 a	58.8 a	58.9 a

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Growth index = [(plant width + plant width perpendicular to first plant width + plant height) / 3]

[x]Means within the same row for each species with the same letters are not significantly different from each other. Means separated by t-test ($p = 0.05$). n =18.

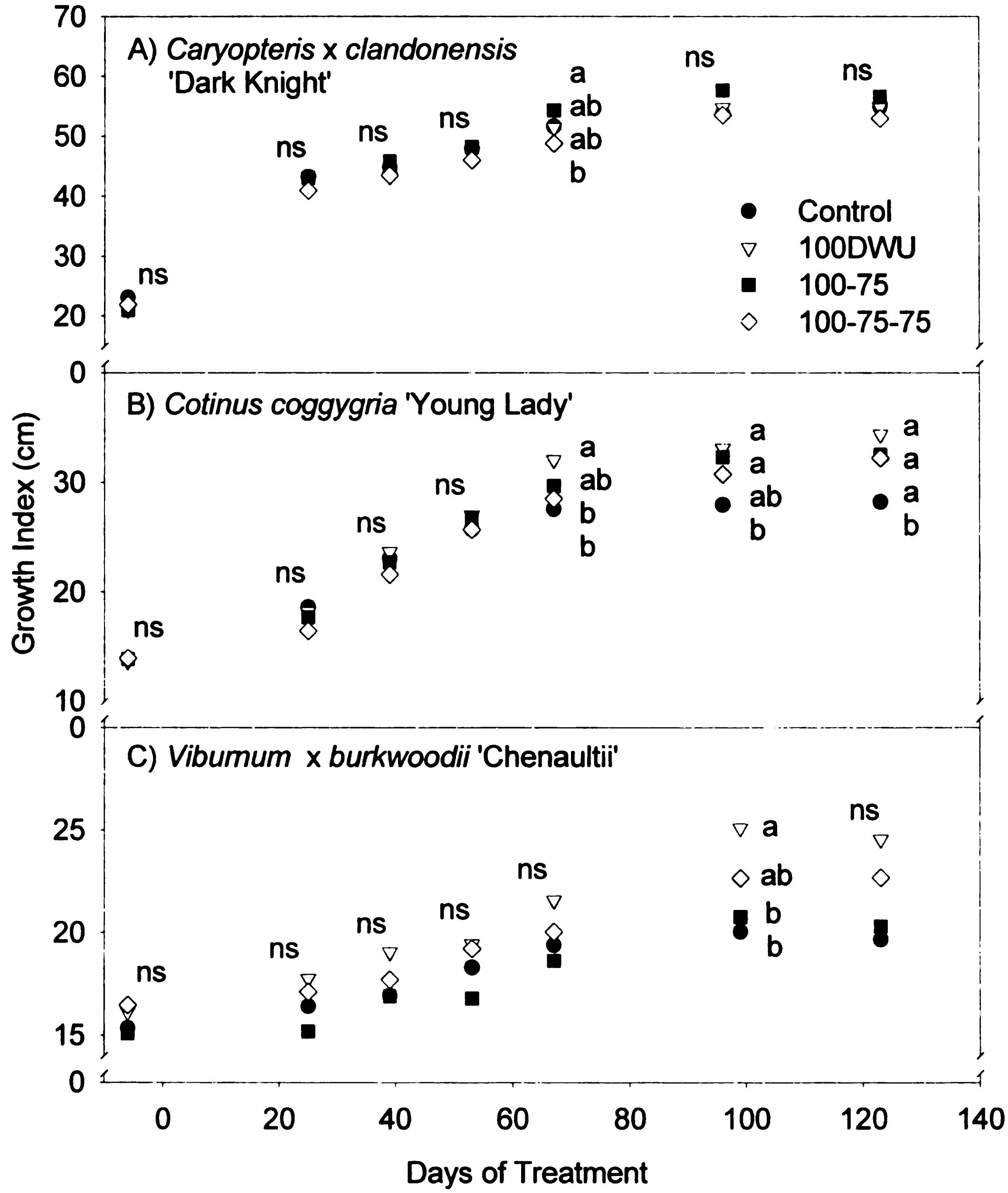

Figure 1.11. Growth index of 3 container-grown woody ornamentals under four irrigation treatments applied from 8 June to 13 October, 2007. Note different y-axis scales. Day 0 = 7 June. Within each day treatment means followed by the same letter are not significantly different (t-test, α = 0.05). ns = not significant. n = 18.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

In 2006 and 2007 irrigation volume affected the final GI of *C. dichotoma* 'Early Amethyst', a high water user, and *C. coggygria* 'Young Lady', *D. gracilis* 'Duncan', *S. ×prestoniae* 'Donald Wyman', and *T. plicata* 'Atrovirens' which were low water users. Average DWU of these four low water users was 56% to 70% less than the control under the 100DWU treatment (Figures 1.3 and 1.5). The lower final GI of control plants was likely a result of higher irrigation volumes leaching nutrients out of the substrate. However, no nutrient deficiency symptoms were observed for these species. Average DWU of another low water user, *V. dentatum* 'Ralph Senior' was 69% less than the control (Figure 1.3), and although final GI was not affected by irrigation volume, leaves of control plants were chlorotic by the end of the study indicating possible nutrient deficiencies.

In addition to reducing over-watering compared to a fixed irrigation rate, irrigating based on DWU ensures that adequate water is supplied to plants during periods of increased water use. *C.* dichotoma 'Early Amethyst', *C. ×clandonensis* 'Dark Knight', *F. ×intermedia* 'New Hampshire Gold', *H. paniculata* 'Unique', *S. fritschiana* 'Wilma', and *W. florida* 'Alexandra' all had DWU values that exceeded the control on at least one measurement day during the experiment (Figures 1.2A and 1.4A,C,E,G, and J). During these periods water applied by the control was not enough to meet the DWU of these species. This shows that in addition to over-watering a fixed irrigation schedule may also lead to under-watering with the potential to create water deficits in container substrate during extended periods of high water demand.

Beeson (2006) showed strong relationships between cumulative actual evapotranspiration (ET_A) and plant growth using different levels of management allowed deficit irrigation (MAD). He concluded that restrictive irrigation regimens such as high MAD levels will lengthen production times by reducing the rate of plant growth, and the additional irrigation required during the extended period may exceed the irrigation applied by the less-restrictive irrigation schedules. In the current experiment, plant growth rate was determined by subtracting initial GI from final GI and the increase in GI during the experiment was compared among treatments for all species in 2006 and 2007. There was no evidence that irrigating according to the DWU treatments in the current study would increase production time as there was no affect of irrigation treatment on GI increase for any species, except *T. plicata* 'Atrovirens' where GI increase of the 100DWU treatment was greater than the control (data not shown).

Internode Length

Irrigation volume did not affect internode length for 16 of the 17 species measured ($p < 0.05$). For *C. coggygria* 'Young Lady' the difference in internode length was minimal at ≤ 0.05 cm between all treatments (data not shown). With no practical difference in internode length among treatments it can be concluded that irrigation treatments did not affect shoot expansion.

Leaf Area

Average leaf area of *T. plicata* 'Atrovirens' (2006) and *T. occidentalis* 'Techny' (2007) was not measured. There was no effect of irrigation treatment on average leaf area for any species during 2006 (data not shown). The only differences in average leaf area among treatments for species in 2007 were for *C.* × *clandonensis* 'Dark Knight' and *W. florida* 'Alexandra' with average leaf area of the 100-75 treatment greater than the control for both species. Leaf area for the control, 100DWU, 100-75, and 100-75-75 treatments for *C.* × *clandonensis* 'Dark Knight' were 4.32; 4.76; 5.33; and 4.95 cm^2, respectively, and for *W. florida* 'Alexandra' were 18.26; 20.43; 23.50; and 22.47 cm^2, respectively. While reduction in leaf area is one effect of water stress (Kozlowski et al., 1991), average leaf area of the restrictive 100-75 and 100-75-75 treatments were the same or higher for the 17 species measured.

DWU treatments either increased or did not affect plant growth compared to the control for all species, while conserving significant amounts of water. Other studies have reported substantial reductions in irrigation with a minimal to no effect on growth. Welsh et al. (1991) reported that *Photina* × *fraseri* irrigated with 100%, 75%, and 50% replacements of actual water use did not differ in water use, shoot extension, shoot dry weight, leaf number, average leaf area, and root area. Tyler et al. (1996) reported that a 44% reduction in irrigation volume resulted in top dry weight and total plant dry weight losses of only 8% and 10% for *Cotoneaster dammeri* 'Skogholm'. Groves et al. (1998a) reported similar results with a 40% reduction in irrigation volume resulting in the production of 90% dry weight of *C. dammeri* 'Skogholm'. These studies show that substantial reductions in irrigation are possible with little to no reductions in growth, even when irrigation is applied at slight deficits of daily water use.

Water Use Efficiency

Using a method similar to Knox (1989), plant water use efficiency was estimated by dividing the increase in growth index (cm) during the experiment by total water volume applied (irrigation plus precipitation; $L \cdot container^{-1}$). Our estimate of WUE does not take into account differences in DWU among treatments of the same species because DWU measurements used to schedule irrigation applications were based on DWU of control plants only. Additionally, water losses from leaching, drift, and canopy shedding were not measured. Irrigation applied to plants in the control treatment was usually in excess of plant DWU, therefore WUE of the control treatment was expected to be lower than DWU treatments.

For 2006 WUE of the control was lowest among treatments for *C. dichotoma* 'Early Amethyst', *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', *S. × doorenbosii* 'Kordes', *T. plicata* 'Atrovirens' and *V. dentatum* 'Ralph Senior' (Table 1.5). For *C. sericea* 'Farrow' WUE of the control was lower than the 100-75 and 100-75-75 treatments, and for *Syringa × hyacinthiflora* 'Asessippi' WUE of the control treatment was lower than the 100-75-75 and 100DWU treatments (Table 1.5). Water use efficiency did not differ among treatments for *Viburnum* *opulus* 'Roseum', even though WUE of the three DWU treatments was approximately three times higher than the control treatment (Table 1.5).

Water use efficiency among species for the control, 100DWU, 100-75, and 100-75-75 treatments ranged from 0.06 to 0.36; 0.17 to 0.79; 0.13 to 0.69; and 0.18 to 0.82, respectively, (Table 1.5). Among species for the control treatment the high water user *C. dichotoma* 'Early Amethyst' used water the most efficiently (Table 1.5). The low water user, *K. japonica* 'Albiflora', was the most efficient water user among species in the 100DWU and 100-75-75 treatments (Table 1.5). *K. japonica* 'Albiflora' and *C. dichotoma* 'Early Amethyst' were the two most efficient water users in the 100-75 treatment (Table 1.5). *T. plicata* 'Atrovirens' was the least efficient water user in the control treatment (Table 1.5).

In 2007 WUE of the control treatment was lowest among treatments for all species except *T. occidentalis* 'Techny' and *V.* ×*burkwoodii* 'Chenaultii' (Table 1.6). For *T. occidentalis* 'Techny' WUE of the 100-75 treatment was higher than the control. For *V.* ×*burkwoodii* 'Chenaultii', the 100DWU treatment had a higher WUE than plants in the control. Tyler et al. (1996) reported irrigation use efficiency of *Cotoneaster dammeri* 'Skogholm' grown under a low leaching fraction (LF) of 0.0 to 0.2 was 29% higher than a high LF of 0.4 to 0.6. Groves et al. (1998b) also reported higher irrigation efficiencies with lower irrigation volumes for *C. dammeri* 'Skogholm' and *Rudbeckia fulgida* 'Goldstrum'. Results of these studies support the higher WUE values of the DWU treatments compared to the control for the majority of species in the current study.

Table 1.5. Estimated water use efficiency (WUE) and water use classification (H = High, M = Moderate, L = Low) of 9 container-grown woody ornamentals under 4 irrigation regimes from 14 June to 13 October 2006. WUE was estimated as increase in growth index (GI) per liter of total water applied. Total water applied included irrigation plus precipitation in liters per container.

Species	Water Use Efficiency				Water Use Class
	Control[z]	100DWU	100-75	100-75-75	H, M, L
Callicarpa dichotoma 'Early Amethyst'	0.36b[y]A[x]	0.59aB	0.61aA	0.64aB	H
Kerria japonica 'Albiflora'	0.24bB	0.79aA	0.69aA	0.82aA	L
Cornus sericea 'Farrow'	0.16bC	0.33 abDC	0.37aBC	0.40aC	M
Symphoricarpos x *doorenbosii* 'Kordes'	0.16bC	0.30aD	0.36aBC	0.39aC	L
Deutzia gracilis 'Duncan'	0.12bCD	0.41aD	0.40aB	0.43aC	L
Syringa x *hyacinthiflora* 'Asessippi'	0.06cDE	0.27abDE	0.13bcD	0.32aCD	L
Viburnum dentatum 'Ralph Senior'	0.06bDE	0.21aDE	0.22aCD	0.24aDE	L
Viburnum opulus 'Roseum'	0.06aDE	0.17aE	0.17aD	0.18aE	L
Thuja plicata 'Atrovirens'	0.04bE	0.21aDE	0.17aD	0.19aDE	L

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU the second application and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Means with the same lowercase letters within the same row are not significantly different. Means separation by Tukey's Test (α = 0.05). n = 18

[x]Means with the same uppercase letters within the same column are not significantly different. Means separation by Tukey's Test (α = 0.05). n = 18.

Table 1.6. Estimated water use efficiency (WUE) and water use classification (H = High, M = Moderate, L = Low) of 10 container-grown woody ornamentals under 4 irrigation regimes from 8 June to 13 October 2007. WUE was estimated as increase in growth index (GI) per liter of total water applied. Total water applied included irrigation plus precipitation in liters per container.

Species	Water Use Efficiency				Water Use Class
	Control[z]	100DWU	100-75	100-75-75	H, M, L
Forsythia x *intermedia* 'New Hampshire Gold'	0.39c[y]A[x]	0.52bA	0.63aA	0.61aA	H
Hydrangea paniculata 'Unique'	0.26cB	0.37bB	0.44ab	0.42ab	H
Weigela florida 'Alexandra'	0.22cBC	0.32bCB	0.37abBC	0.39aB	H
Hydrangea arborescens 'Dardom'	0.22cC	0.33bCB	0.37abBC	0.41aB	M
Caryopteris x *clandonensis* 'Dark Knight'	0.21bC	0.29aCD	0.34aCD	0.31aC	H
Spiraea fritschiana 'Wilma'	0.16bD	0.24aD	0.25aE	0.31aC	H
Rosa 'Winnipeg Parks'	0.15bD	0.28aCD	0.30aCDE	0.30aC	M
Cotinus coggygria 'Young Lady'	0.09bE	0.27aCD	0.27aDE	0.28aC	L
Thuja occidentalis 'Techny'	0.05bF	0.09abE	0.12aF	0.09abD	M
Viburnum x *burkwoodii* 'Chenaultii	0.03bF	0.14aE	0.10abF	0.12abD	L

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Means with the same lowercase letters within the same row are not significantly different. Means separation by Tukey's Test (α = 0.05). n = 18

[x]Means with the same uppercase letters within the same column are not significantly different. Means separation by Tukey's Test (α = 0.05). n = 18.

In 2007 WUE among species for the control, 100DWU, 100-75, and 100-75-75 treatments ranged from 0.03 to 0.39; 0.09 to 0.52; 0.10 to 0.63; and 0.09 to 0.61; respectively (Table 1.6). Of the 10 species, the high water user *F. × intermedia* 'New Hampshire Gold' was the most efficient water user in all treatments (Table 1.6). The two least efficient water users among species in all treatments were *T. occidentalis* 'Techny' a moderate water user and *V. × burkwoodii* 'Chenaultii' a low water user.

Because there were no differences in GI increase among treatments for any species in 2006 and 2007, except *T. plicata* 'Atrovirens', WUE was primarily affected by differences in total water applied. *F. × intermedia* 'New Hampshire Gold', *H. arborescens* 'Dardom', *H. paniculata* 'Unique' , and *W. florida* 'Wilma' had higher WUE values at lower irrigation treatments with no differences in GI or GI increase. Because these species produced the same amount of growth from less applied water, it may be possible to further reduce irrigation applications before affecting growth.

Water use efficiency among species varied within each water use classification when looking at the 100DWU treatment. *K. japonica* 'Albiflora' was in the low water use group and had a WUE of 0.79 (Table 1.5). In contrast, WUE of another low water user *V. × burkwoodii* 'Chenaultii' was only 0.14 (Table 1.6). The range of WUE values among moderate water users was 0.09 to 0.33 for *H. arborescens* 'Dardom' and *T. occidentalis* 'Techny' (Tables 1.5 and 1.6). Species in the high water use group had WUE values that ranged from 0.24 to 0.59 for *C. dichotoma* 'Early Amethyst' and *S. fritschiana* 'Wilma'(Tables 1.5 and 1.6). The wide range of WUE estimates reported within a water use group in this study is supported by Knox (1989) who showed that water use is influenced by species and plant size and by Still and Davies (1993) who reported different WUE values among species in the same water use classifications.

Still and Davies (1993) reported that growers tended to correlate water use of container-grown ornamentals with plant size. While plant size has been shown to influence water use (Knox, 1989), scheduling irrigation based on plant size alone without considering water use can lead to over-watering. Of the eight species evaluated by Still and Davies (1993), only two species were in the same water use category as initially classified by growers. *Ligustrum japonicum* was rated as a heavy water user by producers prior to the experiment, but had one of the lowest total water consumptions and lowest WUE values of the species in the study. Although species in the current study were not assigned a water use category prior to the experiment, results similar to those by Still and Davies (1993) could be expected if water use classification was based on plant size alone. In the 100DWU treatment *H. paniculata* 'Unique' and *K. japonica* 'Albiflora' had final growth indices of 63 cm and 68 cm, but *H. paniculata* 'Unique', a high water user, used more than twice as much water as *K. japonica* 'Albiflora', a low water user (Tables 1.3 and 1.4; Figures 1.3 and 1.5). These examples show the importance of using actual water use data for irrigation scheduling, instead of perceived water use made from associations based on plant size.

Substrate Electrical Conductivity and pH

Leachate electrical conductivity (EC) of *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* × *burkwoodii* 'Chenaultii' was measured once per month during June, July, August, and September during 2007. High initial EC values in June were likely a result of substrate drying and subsequent buildup of soluble salts during the winter when irrigation was not applied and limited plant uptake due to small plant size (Figure 1.12A – C). On day 48 EC of the control treatment was highest among treatments for *H. arborescens* 'Dardom', and on day 106 EC of the control and 100DWU treatments were higher than the 100-75 and 100-75-75 treatments (Figure 1.12A). Leachate EC of the 100DWU and 100-75-75 treatments were higher than the control for *V.* × *burkwoodii* 'Chenaultii' on day 14, with no other differences (Figure 1.12C).

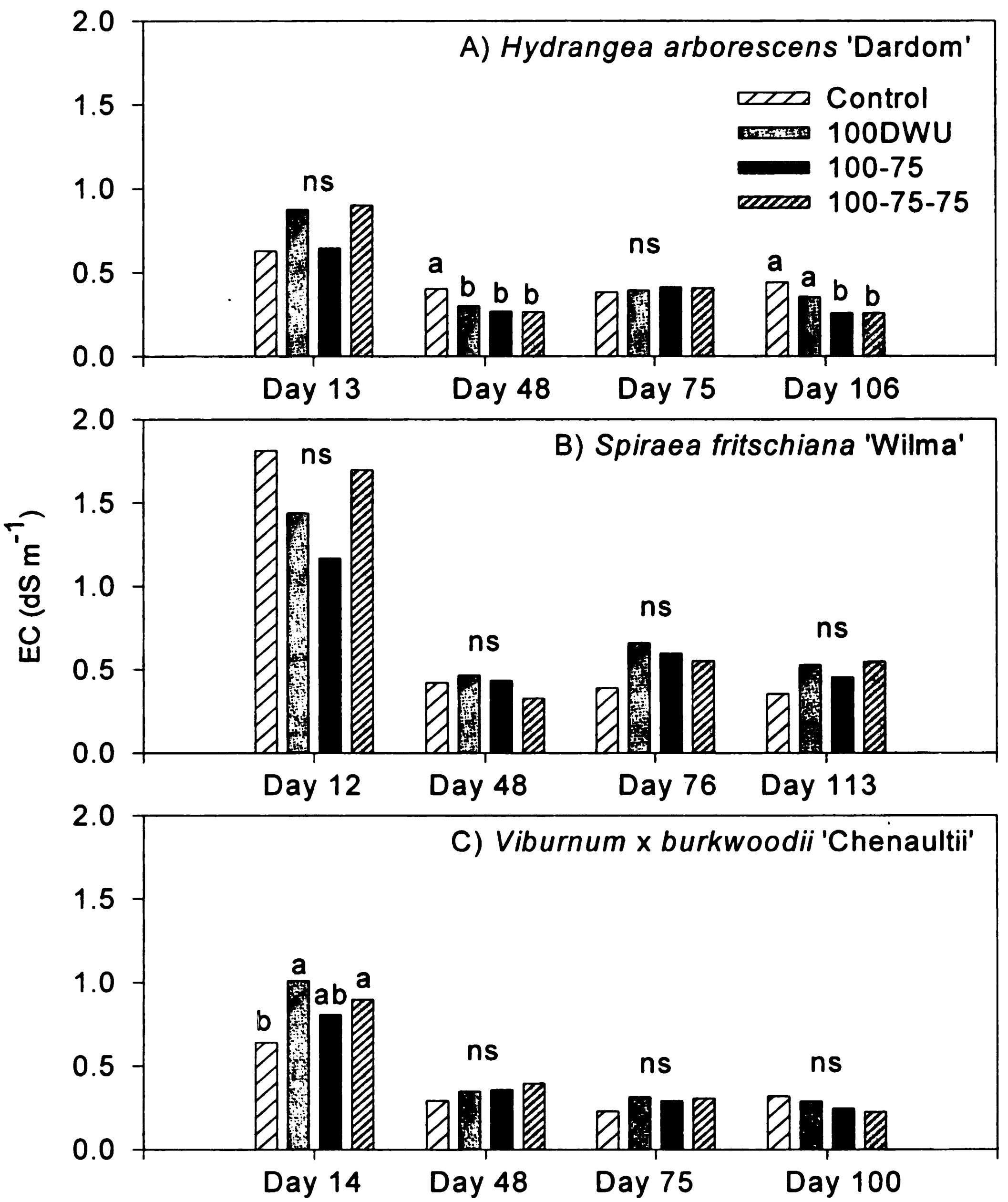

Figure 1.12. Leachate electrical conductivity (EC) ($dS{\cdot}m^{-1}$) of three species of container-grown woody ornamentals under four irrigation treatments on four days during 2007. Within each day treatment means followed by the same letter are not significantly different (t-test, $\alpha = 0.05$). ns = no significant difference between treatments. n = 18.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

A concern when scheduling irrigation at or below DWU is that leaching fractions will be close to zero and may cause EC levels to increase to above recommended levels if precipitation or a periodic increase in irrigation to flush excess salts from the substrate does not occur. Recommended levels of EC when using the pour-thru technique for container-grown plants with only controlled-released fertilizers should range from 0.2 to 0.5 $dS \cdot m^{-1}$ for pine bark substrates (Yeager et al., 1997). Although there were differences in EC levels among treatments on days 48 and 106 for *H. arborescens* 'Dardom', EC levels of all treatments were within the recommended range of 0.2 to 0.5 $dS \cdot m^{-1}$ (Figure 1.12A). Leachate EC levels of *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* ×*burkwoodii* 'Chenaultii' did not exceed recommended levels in any treatment during the experiment. The effect of irrigation volume alone on leachate EC levels could not be determined because precipitation was not excluded from the experiment.

During a 38 day period from day 21 to day 58 only 12.45 mm of precipitation occurred. During this period the largest precipitation event was 3.56 mm on day 46 (Figure 1.2B). On day 48 leachate EC values of the three DWU treatments for the three species were not above the recommended range and were not higher than the control treatment. Even though leachate EC levels of the three DWU irrigation regimes did not increase above recommended levels, monitoring EC levels under any irrigation regime remains an important management tool for assessing nutritional status of container-grown crops. In the event that soluble salt accumulation becomes a concern growers can periodically increase irrigation volume to flush excess soluble salts from the substrate.

Leachate pH of *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V. × burkwoodii* 'Chenaultii' was measured on the same days as EC. Irrigation volume effect was minimal as there were no differences among treatments except for day 48 when leachate pH of the control was lowest among treatments for *H. arborescens* 'Dardom' and *V. × burkwoodii* 'Chenaultii' (data not shown).

Foliar Nutrient Content

Leaves of *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V. × burkwoodii* 'Chenaultii' were collected on days 48 and 92. No deficiency symptoms were observed on any of the 10 species grown during 2007, but chlorosis of leaves of *V. dentatum* 'Ralph Senior' in the control were observed during the 2006 growing season. The number of leaves collected from the three reps per treatment was enough for only one sample per treatment, therefore statistical analysis could not be conducted. General patterns of foliar nutrient content among treatments and species were examined for possible effects by irrigation.

Table 1.7. Foliar nutrient content of three container-grown woody ornamentals under four irrigation regimes on days 48 and 92.

	Foliar Nutrient Content				Recommended
	Control[z]	100DWU	100-75	100-75-75	Range[y]
Hydrangea Arborescens 'Dardom'					
Day 48					
N (%)	1.59	1.56	1.60	1.74	2 – 4.5
P (%)	0.14	0.19	0.18	0.20	0.2 – 0.6
K (%)	0.84	1.39	1.39	1.73	1.5 – 3.5
Day 92					
N (%)	0.99	1.05	0.99	1.17	
P (%)	0.11	0.14	0.14	0.15	
K (%)	0.61	0.73	0.86	1.06	
Spiraea fritschiana 'Wilma'					
Day 48					
N (%)	1.92	2.05	2.12	2.26	2 – 4.5
P (%)	0.20	0.26	0.25	0.25	0.2 – 0.6
K (%)	0.82	1.00	0.90	0.87	1.5 – 3.5
Day 92					
N (%)	1.41	1.51	1.62	1.63	
P (%)	0.14	0.14	0.15	0.16	
K (%)	0.47	0.46	0.57	0.58	
Vibumum × burkwoodii 'Chenaultii'					
Day 48					
N (%)	1.88	1.78	1.81	1.83	2 – 4.5
P (%)	0.22	0.28	0.26	0.29	0.2 – 0.6
K (%)	0.96	1.07	1.14	1.06	1.5 – 3.5
Day 92					
N (%)	1.53	1.68	1.63	1.71	
P (%)	0.17	0.29	0.23	0.30	
K (%)	0.96	1.00	1.10	0.97	

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y] General recommended range of foliar nutrient content for woody plants from (Plank 2008).

Foliar content of Nitrogen (N), Phosphorus (P), and Potassium (K) tended to increase or remain the same with decreasing irrigation treatments for *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* × *burkwoodii* 'Chenaultii' on days 48 and 92 (Table 1.7). For *H. arborescens* 'Dardom', *S. fritschiana* 'Wilma', and *V.* × *burkwoodii* 'Chenaultii' foliar N, P, and K of each treatment tended to be lower on day 92 than day 48 (Table 1.7). This was likely due to controlled release fertilizers being used up as the growing season progressed. Foliar content of Sodium (Na), Sulfur (S), Zinc (Zn), Manganese (Mn), Copper (Cu), Boron (B), and Aluminum (Al) followed the same general trends among treatments and on days 92 and 48 as N, P, and K (Table AB1 – AB3). One exception was AL which was higher on day 92 than 48 for *H. arborescens* 'Dardom' and *S. fritschiana* 'Wilma' (Table AB1 and AB2). Calcium (Ca), Magnesium (Mg), and Iron (Fe) were present in irrigation water and therefore were higher or nearly the same in the control treatment compared to DWU treatments for the three species sampled (Table AB1 – AB3). On day 92 foliar Ca, Mg, and Fe content of all treatments of *H. arborescens* 'Dardom' and *S. fritschiana* 'Wilma' tended to be higher than on day 48 likely due to increasing cumulative irrigation throughout the growing season (Table AB1 and AB2). However, foliar Ca, Mg, and Fe of all treatments for *V.* × *burkwoodii* 'Chenaultii' on day 92 tended to lower than on day 48 (Table AB3). Leaves of *V.* × *burkwoodii* 'Chenaultii' are pubescent and could have limited foliar uptake of these nutrients by preventing direct contact of irrigation water with the leaf surface.

Foliar content of N, P, and K were on the low end or below recommended ranges for woody plants according to the Plant Analysis Handbook of Georgia (Plank, 2008). However, foliar N, P, and K content were similar to those reported by Keever and Cobb (1985) of *Rhododendron* × 'Hershey's Red' irrigated with overhead irrigation applications of 1.3 $cm \cdot ha^{-1} \cdot d^{-1}$, and with intermittent irrigation that provided an additional 0.5 $cm \cdot ha^{-1} \cdot d^{-1}$. While the effect of irrigation volume on foliar N, P, and K content could not be statistically analyzed in the current experiment other studies have reported variable effects of irrigation volume on foliar content of N, P, and K. Groves et al. (1998a) showed that nitrogen content of *Cotoneaster dammeri* 'Skogholm' was not affected by irrigation volume while Jarrell et al. (1983) reported higher N tissue concentrations in *Ligustrum texanum* irrigated with a low leaching fraction (0.1 – 0.2) compared to a high leaching fraction (0.25 – 0.4). Jarrell et al. (1983) attributed results to 2 factors: 1. more N remained in the substrate with less water applied and 2. the majority of plants in the high leaching fraction treatment were larger therefore diluting absorbed N. Groves et al. (1998a) reported P content in tops of *Cotoneaster dammeri* 'Skogholm' decreased with increasing irrigation volume. Groves et al. (1998 a) reported that K content was controlled-release fertilizer dependant and increased, decreased, or showed no trend with increasing irrigation volume depending on the controlled-release fertilizer source.

Conclusions

Scheduling irrigation based on DWU conserved water for all species measured from June through mid-October during 2006 and 2007 when compared to 19 mm-ha·application^{-1} while improving or not affecting plant growth. Water volume conserved compared to the control was 27% to 75% depending on treatment and species. Species were classified as low, moderate, and high water users based on average DWU and total water use. These classifications allow grouping species with similar water requirements together to minimize over-watering. The method used to measure DWU in this study can be used by researchers and growers to quantify water requirements of woody ornamentals not yet evaluated so that plants can be classified according to water use.

Final GI, internode length, and average leaf area of DWU treatments of all species were greater or equal to the control treatment. Additionally greater nutrient losses from container substrates resulting from higher irrigation volumes have been documented by Tyler et al. (1996) and Warsaw (Chapter 2). Fare et al. (1994) reported that NO_3-N losses through leaching were 63% and 19% of total applied N at irrigation depths of 13 mm and 6 mm, respectively. Leaching of nutrients caused by irrigation volumes in excess of DWU would explain growth reductions that occurred in this study for plants in the control treatment.

All three DWU treatments conserved water compared to the control, and the decision on which method a grower would use to schedule irrigation will depend on a number of factors. The ideal irrigation regimen should provide the most economical balance between crop returns and cost of irrigation, which ultimately will vary with crop and water availability for a specific location (Welsh and Zajicek; 1993). Additionally, the cost of water, type of irrigation system, and programming capabilities of the system will partially dictate the irrigation regimen used. For example, a nursery in close proximity to a large urban area in a state where water use and runoff qualities are highly regulated may use the 100-75 or 100-75-75 irrigation schedules to minimize water extraction and runoff. The goal of water conservation irrigation scheduling should be to base irrigation applications on plant demand and to group plants with similar water uses together. Scheduling irrigation according to plant DWU substantially reduced the amount of irrigation applied while producing larger or similar sized plants for the 20 species of container-grown ornamentals in this experiment.

Literature Cited

Anonymous. 2000. Official methods of analysis. 17th ed. AOAC International. Gaithersburg, MD.

Anonymous. 1999. ThetaProbe soil moisture sensor. User Manual ML2-UM-1.21. Delta-T Devices Ltd. Cambridge, England.

Beeson, Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hort. 22(2):113 – 115.

Beeson, Jr., R.C. 2006. Relationship of plant growth and actual evapotranspiration to irrigation frequency based on management allowed deficits for container nursery stock. J. Amer. Soc. Hort. Sci. 131(1):140 – 148.

Bilderback, T.E. 2001. Using the PourThru Procedure for checking the EC and pH for nursery crops. Horticulture Information Leaflet-401, North Carolina

Cornejo, C., D.Z. Haman, and T.H. Yeager. 2005. Evaluation of soil moisture sensors, and their use to control irrigation systems for containers in the nursery industry. ASAE Meeting Paper No. 054056. St. Joseph, MI: ASAE.

Fare, D.C., C.G. Gilliam, and G.J. Keever. 1993. Monitoring irrigation at container nurseries. Hort. Technology 2:75 – 78.

Fare, D.C., C.H. Gilliam, G.J. Keever, and J.W. Olive. 1994. Cyclic irrigation reduces container nitrate-nitrogen concentration. HortScience. 29(12):1514 – 1517.

Garcia y Garcia, A., G. Hoogenboom, and L. Guerra. 2004. Container temperature and moisture for estimating evapotranspiration of nursery crops. ASAE/CSAE Meeting Paper No. 042295. St. Joseph, Mich. ASAE.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998 a. Irrigation volume, application, and controlled-release fertilizers: I. Effect on plant growth and mineral nutrient content in containerized plant production. J. Environ. Hort. 16(3):176 – 181.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998 b. Irrigation volume, application, and controlled-release fertilizer II. Effect on substrate solution nutrient concentration and water efficiency in containerized plant production. J. Environ. Hort. 16(3):182 – 188.

Jarrell, W.M., S.J. Whaley, and B. Miraftabi. 1983. Slow-release fertilizer and water management with container-grown *Ligustrum texanum*. Scientia Hort. 19:177 – 190.

Keever, G.J. and G.S. Cobb. 1985. Irrigation scheduling effects on container media and canopy temperatures and growth of 'Hershey's Red' Azalea. HortScience 20(5):921 – 923.

Kincaid, D.C., and D.F. Heerman. 1974. Scheduling irrigations using a programmable calculator. USDA-ARS-NC-12. Washington, D.C.: U. S. Gov. Print Office.

Knox, G.W. 1989. Water use and average growth index of five species of container-grown woody landscape plants. J. Environ. Hort. 7(4):136 – 139.

Kozlowski, T.T., P.J. Kramer, and S.G. Pallardy. 1991. The Physiological Ecology of Woody Plants. Academic Press, New York.

Plank, C.O. 2008. Plant Analysis Handbook of Georgia. The University of Georgia. College of Agricultural and Environmental Sciences. Cooperative Extension Service. Webpage:
http://aesl.ces.uga.edu/publications/plant/index.htm
Accessed: 04/23/2008

Still, D.W. and F.T. Davies, Jr. 1993. Water use, water use efficiency and growth analysis of selected woody ornamental species under a non-limiting water regime. Scientia Hort. 53 (1993) 213 – 223.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. J. Environ. Hort. 14(4):199 – 204.

Weatherspoon, D.M. and C.C. Harrell. 1980. Evaluation of drip irrigation for container production of woody landscape plants. HortScience. 15(4):488 – 489.

Welsh, D.F., J.M. Zajicek, C.G. Lyons, Jr. 1991. Effect of seasons and irrigation regimes on plant growth and water-use of container-grown *Photina x fraseri*. J. Environ. Hort. 9(2):79 – 82.

Welsh, D.F. and J.M. Zajicek. 1993. A model for irrigation scheduling in container-grown nursery crops utilizing management allowed deficit (MAD) J. Environ. Hort. 11(3): 115 – 118.

Yeager, T., C. Gilliam, T. Bilderback, D. Fare, K. Tilt, and A. Niemiera. 1997. Best management practices guide for producing container-grown plants.

Southern Nursery Association, 1000 Johnson Ferry Road, Suite E-130, Marietta, GA 30068 – 2100.

Yeager, T.H. 2003. Implementation guide for container-grown plant interim Measure. EDIS Document ENH-895. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage: http://edis.ifas.ufl.edu/EP152 Accessed 01/23/2008.

CHAPTER TWO

CONTAINER-GROWN ORNAMENTAL PLANT GROWTH AND WATER RUNOFF VOLUME AND NUTRIENT CONTENT UNDER FOUR IRRIGATION TREATMENTS

CONTAINER-GROWN ORNAMENTAL PLANT GROWTH AND WATER RUNOFF VOLUME AND NUTRIENT CONTENT UNDER FOUR IRRIGATION TREATMENTS

Abstract

Irrigating container-grown woody ornamentals according to daily water use (DWU) was compared to a traditional irrigation rate to determine reductions in irrigation volumes, runoff, and nutrient losses from container production beds. *Deutzia gracilis* Sieb. and Zucc. 'Duncan', *Kerria japonica* (L.) DC. 'Albiflora', *Thuja plicata* D. Don. 'Atrovirens', and *Viburnum dentatum* L. 'Ralph Senior' were grown in 10.2 L (# 3) containers under four overhead irrigation regimes: 1. a control irrigation rate of 19 mm-ha·application^{-1}; 2. irrigation scheduled to replace 100% daily water use per application (100DWU); 3. irrigation alternating every other application with 100% replacement of DWU and 75% DWU (100-75); and 4. irrigation scheduled on a three application cycle with one application of 100% DWU followed by two applications replacing 75% DWU (100-75-75). Treatments were applied from 8 June through 30 Sept. 2007. Plants used were from a previous irrigation experiment conducted in 2006 and received the same irrigation treatments during the 2006 growing season. Total irrigation applied for the 100DWU, 100-75 and 100-75-75 treatments was 33%, 41%, and 44% less than the control. Plants grown under the 3 DWU treatments had a final growth index greater than or equal to the control treatment depending on species. Runoff volume, NO_3^--N and PO_4^{3-}-P content was determined on 2 days per month, one day when DWU treatments were applied at 100% DWU and the

second when the 100-75 and 100-75-75 treatments were both applied at 75% DWU. Irrigating according to the DWU treatments used in this study reduced irrigation and runoff volumes, and NO_3^--N and PO_4^{3-}-P losses compared to a control of 19 mm-ha while producing the same size or larger plants.

Introduction

Container-grown crops are frequently irrigated with large volumes of water during the growing season. Container substrate volumes and substrate components designed to drain quickly limit the amount of water and nutrients available to plant roots for uptake (Dole et al., 1994). However, a large portion of the applied water is not utilized by plants. Weatherspoon and Harrell (1980) reported that as little as 13% to 26% of applied water was retained in the container. Water that misses the container or that is not retained in the container following irrigation is lost resulting in wasted water. Another drawback of irrigation applications that generate runoff is that fertilizers applied to maintain nutrient levels essential for plant growth are leached out of containers and may enter the environment. Nutrient losses from container substrates are a potential threat to surrounding water resources. Fare et al. (1994) reported NO_3^--N losses ranging from 46% to 63% of total applied N when 13 mm of irrigation was applied in three cycles or one cycle. Additionally, phosphorus losses from container substrates ranging from 8% to 27% have been reported by Warren et al. (1995).

Contamination of the environment by nursery runoff is classified as a non-point source of pollution (Fain et al., 2000). Yeager and Cashion (1993) reported nitrate concentrations from controlled-release fertilizers in runoff exceeded the 10 ppm federal drinking water standard as established by the U. S. Environmental Protection Agency in 1982. Concerns about contamination of water resources by nursery runoff have risen as nurseries and urban and suburban areas become closer. Nutrient management laws have been established in Maryland, Delaware, and California that limit nutrient concentrations in runoff (Beeson et al., 2004). In order to meet current legislation, prepare for future legislation, and ease mounting public concern ways to reduce runoff without detracting from plant growth must be found.

One way to reduce runoff is by irrigating according to plant daily water use (DWU), the amount of water lost from plant transpiration and substrate evaporation. This is a key concept in water conserving irrigation scheduling as only the volume of water used by the plant-container-system since the previous irrigation is replaced keeping over-watering to a minimum. An advantage of this approach to irrigation scheduling is that it can be adapted to most irrigation systems. The container-nursery industry evolved in an environment with few restrictions on water use. In addition there are hundreds of different species currently produced in containers. As a result limited research has been undertaken to investigate the DWU of container-grown woody ornamentals and the effects of this type of irrigation scheduling on plant growth, runoff, and nutrient loss. The objectives of this experiment were to determine the effects of scheduling irrigation applications according to DWU or a percentage of DWU on irrigation volume, plant growth, runoff, and nutrient loss compared to a conventional irrigation rate.

Materials and Methods

Site

The experiment was conducted at the Michigan State University Horticulture Teaching and Research Center (HTRC), Holt., MI. The HTRC is at latitude 42.67 degrees, longitude -84.48 degrees, and elevation 264 meters. Plants were grown on 3 m × 6 m nursery production areas designed to collect runoff from the production surface. Production areas were oriented east to west on the long axis. The surface was lined with 6 mil polypropylene plastic and covered with a landscape fabric. Production areas slope toward the center and west end to allow runoff collection in an excavated reservoir. Collection reservoirs consisted of a wooden frame lined with polypropylene pond liner. The twelve production areas used were separated by 3.66 m to minimize effects of irrigation drift. Precipitation was not excluded, but was recorded by a Michigan Automated Weather Network (MAWN) weather station located on-site at the HTRC.

Plant Material

Deutzia gracilis Sieb. and Zucc. 'Duncan', *Kerria japonica* (L.) DC. 'Albiflora', *Thuja plicata* D. Don. 'Atrovirens' and *Viburnum dentatum* L. 'Ralph Senior' plants used in an irrigation experiment in 2006 were grown for a second season in the same 10.2 L containers. Plant material was potted up from 5.7 cm rooted cuttings into 10.2 L containers from 6 – 9 Sept. 2005. Container substrate consisted of 85% pine bark:15% peat moss (vol:vol). Plants were fertilized on 5 June 2006 with 26 g·container^{-1} of a 17.0N–3.5P–6.6K controlled-release fertilizer with micronutrients (Harrell's Inc., Lakeland, FL)., and on 14 May 2007 with 26 g·container^{-1} of a 19.0N–2.2P–7.5K controlled-release fertilizer with Polyon Reactive Layers Coating controlled release technology with nutrient release technology and micronutrients (Harrell's Inc.). Nutrient release period at average media temperatures of 21° C and 27° C is 5 months and 3 – 4 months. All cultural practices were kept identical except irrigation.

Experimental Setup

The experiment was a completely randomized design with subsamples (individual plants). Each plant was irrigated with the same irrigation treatment as the previous year. Irrigation treatments were: 1. a control irrigation rate of 19 mm-ha·application^{-1} (1.07 L·container^{-1}); 2. irrigation scheduled to replace 100% daily water use at each application (100DWU); 3. irrigation alternating every other application with 100% replacement of DWU and 75% DWU the following application (100-75); and 4. irrigation scheduled on a three application cycle replacing 100% DWU followed by two applications of replacing 75% DWU (100-75-75). Irrigation applications were separated by at least 24 h. Irrigation applications were applied once per day from 8 June (day 1) through 30 Sept.

(day 115) 2007. Treatments were replicated three times with six plants of each species per treatment replicate. Plants of all species were randomly arranged in each treatment replicate in three rows of eight. Plants were spaced 45 cm on center. Guard plants in 10.2 L containers were placed around the outside of each treatment replicate to minimize edge effects and spaced 45 cm from experiment plants. Types of guard plants varied within a treatment replicate, but type and order for all treatment replicates were identical.

Daily Water Use

Daily water use (DWU) was measured using a ThetaProbe Type ML2x soil moisture sensor (Delta-T Devices Ltd., Cambridge, U.K.) connected to a ThetaMeter Hand-Held Readout Unit Type HH1 (Delta-T Devices Ltd.). The four sensing rods of the ThetaProbe are 60 mm long. Substrate volumetric moisture content was measured by inserting the rods perpendicular to the substrate surface. Container height was 245 mm. Substrate volumetric moisture content was measured 1 h after irrigation and 24 h later. Measurements of DWU were taken during 24 h periods without precipitation. The percent difference in volumetric moisture content was multiplied by the average volume of container substrate (9.7 $L \cdot container^{-1}$) to determine the volume of water lost. A substrate specific calibration was conducted to improve the accuracy of the ThetaProbe as outlined in the ThetaProbe Type ML2x user manual (Anonymous, 1999). Irrigation rate of the overhead system was measured using eight rain gauges randomly placed throughout an irrigation zone to collect water for 30 min. The irrigation cycle was repeated with the eight rain gauges in different locations for a total of 16 measurements. Irrigation rates from 3 of the 12 production areas were measured in this manner and the average rate was 0.28 $mm \cdot min^{-1}$ (17 $mm \cdot h^{-1}$).

Irrigation Applications

Irrigation applications were scheduled with a Rain Bird ESP-12LX Plus controller (Rain Bird Corporation; Azusa/Glendora, CA). Each treatment replicate was controlled by a solenoid valve. Irrigation was applied through six Toro 570 Shrub Spray Sprinklers (The Toro Company; Riverside, CA) that included two 2.44 m 180° emitters located at the midpoint of each 6 m side of the bed and four 2.44 m 90° emitters located at each corner of the bed. Emitters were positioned on the outside edges of each bed with all irrigation directed inward. Sprinklers were mounted on 1.3 cm diameter risers 0.66 m high. Irrigation treatments based on DWU were applied at the volume corresponding to the species with the highest DWU to avoid under-watering any species. Irrigation was initiated between 0700 HR 0800 HR.

Plant Response to Irrigation Treatments

Effects of irrigation volume on plant growth and container substrate was determined by measuring growth index, leachate electrical conductivity, and leachate pH. A plant growth index (GI) was calculated every two to four weeks during the experiment. Growth index was calculated as [(plant width A + plant width perpendicular to width A + plant height) / 3]. Plant height was measured from the container rim and widths were measured from the same location each time. Plant growth in the current experiment represents the second season of growth under the same irrigation treatments. Leachate electrical conductivity (EC) was measured with a Horiba Cardy Twin EC Meter (Spectrum Technologies, Inc., Plainfield, Illinois), and leachate pH was measured with a Horiba Cardy Twin pH Meter (Spectrum Technologies, Inc.) using the PourThru extraction procedure as described by Yeager (2003). Electrical conductivity and pH data were measured from two plants of each species within each treatment replicate monthly during the experiment.

Runoff Collection

Runoff from each production bed was collected two days per month. Runoff was collected when the three DWU treatments were at 100% DWU and the other day when the 100-75 treatment was at 75% DWU and the 100-75-75 treatment was on the second day of 75% DWU. Runoff was collected by pumping the runoff out of the collection reservoir into a container to measure the volume 0.5 h after irrigation.

Water samples were collected from runoff in each reservoir to determine NO_3^--N and PO_4^{3-}-P concentrations for each treatment. Samples were stored in a cooler at 3°C until analysis. Analysis of runoff water for NO_3^--N and PO_4^{3-}-P content was conducted at the Michigan State University Soil Testing Laboratory (A81 Plant & Soil Sciences Building, Michigan State University, East Lansing, MI) using standard protocols.

Statistical Analysis

Data for each species was analyzed separately except for water use efficiency and average irrigation applied per container. Growth index, pH and EC data were analyzed as repeated measures using the PROC MIXED procedure of SAS (SAS version 9.1; SAS Institute, Cary, NC). When significant, treatment main effects were separated using the PDIFF option of the lsmeans statement ($\alpha = 0.05$). Additionally treatment by day interactions were sliced by day and treatment means were compared on each measurement date using the SLICING option of PROC MIXED and the PDIFF option of the lsmeans statement ($\alpha = 0.05$). Average irrigation applied per container, water use efficiency, runoff volume, NO_3^--N, and PO_4^{3-}-P data were subjected to ANOVA using PROC GLM procedure of SAS (SAS version 9.1; SAS Institute) and when significant means were separated using Tukey's Honest Significance test at the 0.05 level.

Results and Discussion

Water Use

During the 115 day experiment 19 mm-ha·application^{-1} (1.07 L·container^{-1}) of irrigation was applied in the control treatment totaling 2200 mm-ha (123 L·container^{-1} ; Table 2.1). Rainfall during this period was 250 mm and added 14 L to each container (Figure 2.1). Irrigation was not applied when rainfall exceeded 20 mm during a 24 hr period which occurred 4 times during the experiment. Average daily water applied during the experiment for the 100 DWU, 100-75 and 100-75-75 treatments was 33%, 41%, and 44% less than the control (Table 2.1).

Table 2.1. Average water applied ($L \cdot container^{-1} \cdot d^{-1}$) and total water applied ($L \cdot container^{-1}$) from 8 June through 30 September 2007 for *Deutzia gracilis* 'Duncan', *Kerria japonica* 'Albiflora', *Thuja plicata* 'Atrovirens' and *Viburnum dentatum* 'Ralph Senior' grown in 10.2 L containers under 4 irrigation treatments.

Treatment	Average water applied ($L \cdot container^{-1} \cdot d^{-1}$)	Total water applied ($L \cdot container^{-1}$)
Control^z	1.07 ± 0.00^y A^x	123.05
100DWU	0.72 ± 0.02 B	82.42
100-75	0.63 ± 0.02 C	72.35
100-75-75	0.60 ± 0.02 C	68.86

^{z}Control = 1.07 $L \cdot day^{-1}$; 100DWU = 100% daily water use (DWU) per day; 100-75 = 2 day cycle with 100% DWU first day and 75% DWU second day; and 100-75-75 = 3 day cycle 100% DWU the first day followed by two days of 75% DWU. DWU volume applied = highest DWU of the 4 species on each sample date.

^{y}Standard error of treatment means.

^{x}Means separation using Tukey's Test ($\alpha = 0.05$), n = 115.

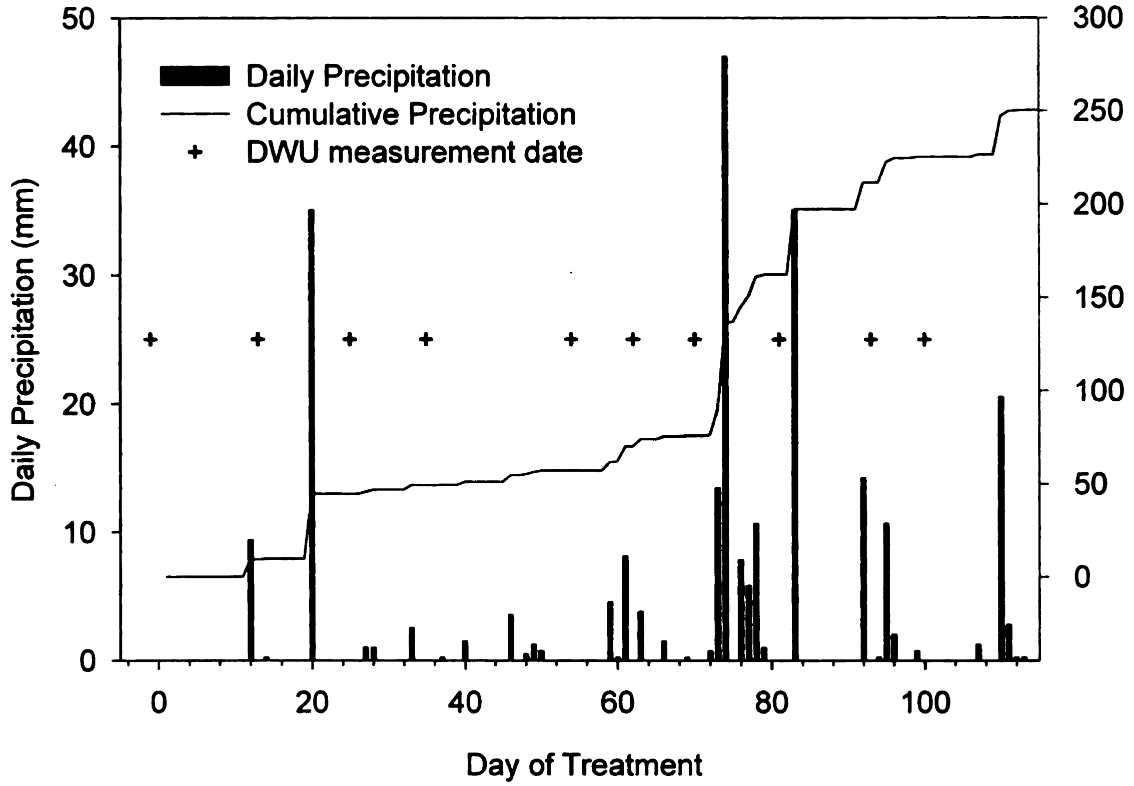

Figure 2.1. Daily (bars) and cumulative precipitation (line) from 8 June (Day 1) to 30 September (Day 115) 2007. Crosshairs indicate dates of DWU measurement. Precipitation data courtesy of Michigan State University and the Enviro-weather project.

Water use of the 4 species was higher in 2007 than in an experiment conducted in 2006 with the same irrigation treatments. Average DWU during the 2006 experiment and the current study in 2007 were 0.3 and 0.61 L·container^{-1} for *D. gracilis* 'Duncan', 0.37 and 0.62 L·container^{-1} for *K. japonica* 'Albiflora', 0.33 and 0.38 L·container^{-1} for *T. plicata* 'Atrovirens', and 0.31 and 0.59 L·container^{-1} for *V. dentatum* 'Ralph Senior' (Chapter 1). Higher DWU in 2007 compared to 2006 was likely due to higher daily reference potential evapotranspiration on DWU measurement days in 2007 compared to 2006 with averages of 4.1 mm and 3.7 mm (data not shown). Additionally, larger plant sizes likely contributed to higher plant water use in 2007. In a previous experiment (chapter 1) *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', and *V. dentatum* 'Ralph Senior' were classified as low water users. Plants were assigned to water use groups based on average DWU and total water applied during the experiments. Using the water use classifications from the previous experiment *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', and *V. dentatum* 'Ralph Senior' were classified as moderate water users in 2007. *Thuja plicata* 'Atrovirens' was classified as a low water user in the previous and current experiments.

Daily water use peaked in late July and early August with the highest DWU of all species occurring on 8 Aug 2007 (Figure 2.2). Average DWU was higher than the control only on 8 Aug. for *D. gracilis* 'Duncan' and *V. dentatum* 'Ralph Senior' with DWUs of 1.24 and 1.23 $L \cdot container^{-1}$ (Figure 2.2). Lowest DWU was recorded on 12 July for *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', and *T. plicata* 'Atrovirens'; and 20 June for *V. dentatum* 'Ralph Senior'.

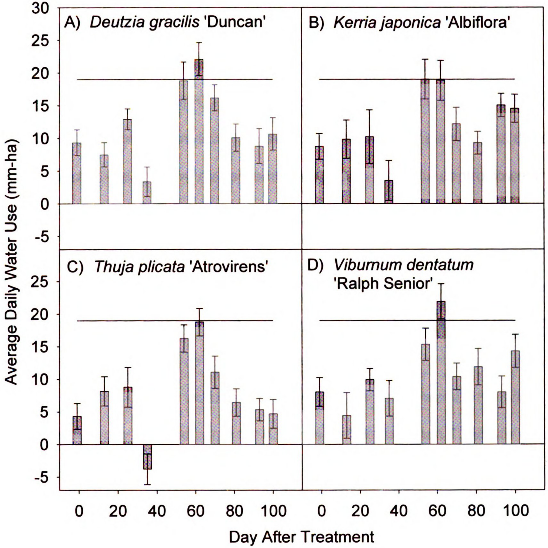

Figure 2.2. Daily water use of four container-grown woody ornamentals from 8 June to 30 September 2007. Bars show daily water use. Error bars represent standard error of means from 18 plants of each species. Horizontal line shows control treatment of 19 mm-ha·application^{-1}. Day 0 = 7 June 2007.

Growth Index

Growth index treatment means were separated by day (Figure 2.3 A – C). Differences in growth index of *D. gracilis* 'Duncan' were first measured on day 55 where GI of the 100 DWU treatment was greatest among treatments

(Figure 2.3A). Final GI of the 100DWU treatment was greater than the 100-75 and control treatments (Figure 2.3A). The final GI (day 109) of *D. gracilis* 'Duncan' in 2007 was identical to final GI response in 2006 (day 127: Chapter 1).

Differences in GI of *K. japonica* 'Albiflora' occurred on the same days as *D. gracilis* 'Duncan' (Figure 2.3B). Effect of irrigation volume on GI was the same on day 55 and the next two measurement days with GI of the control lowest among treatments. During the 2006 study irrigation did not affect final GI (day 132) of *K. japonica* 'Albiflora' (Chapter 1).

For *T. plicata* 'Atrovirens' GI of the 100DWU treatment was higher than the control on each measurement day (Figure 2.3D). Differences on the first measurement day were due to the effect of irrigation treatment from the previous growing season. Growth index response to irrigation treatment by the final measurement day was the same for *K. japonica* 'Albiflora' and *T. plicata* 'Atrovirens' with GI of all DWU treatments greater than the control (Figure 2.3B and C).

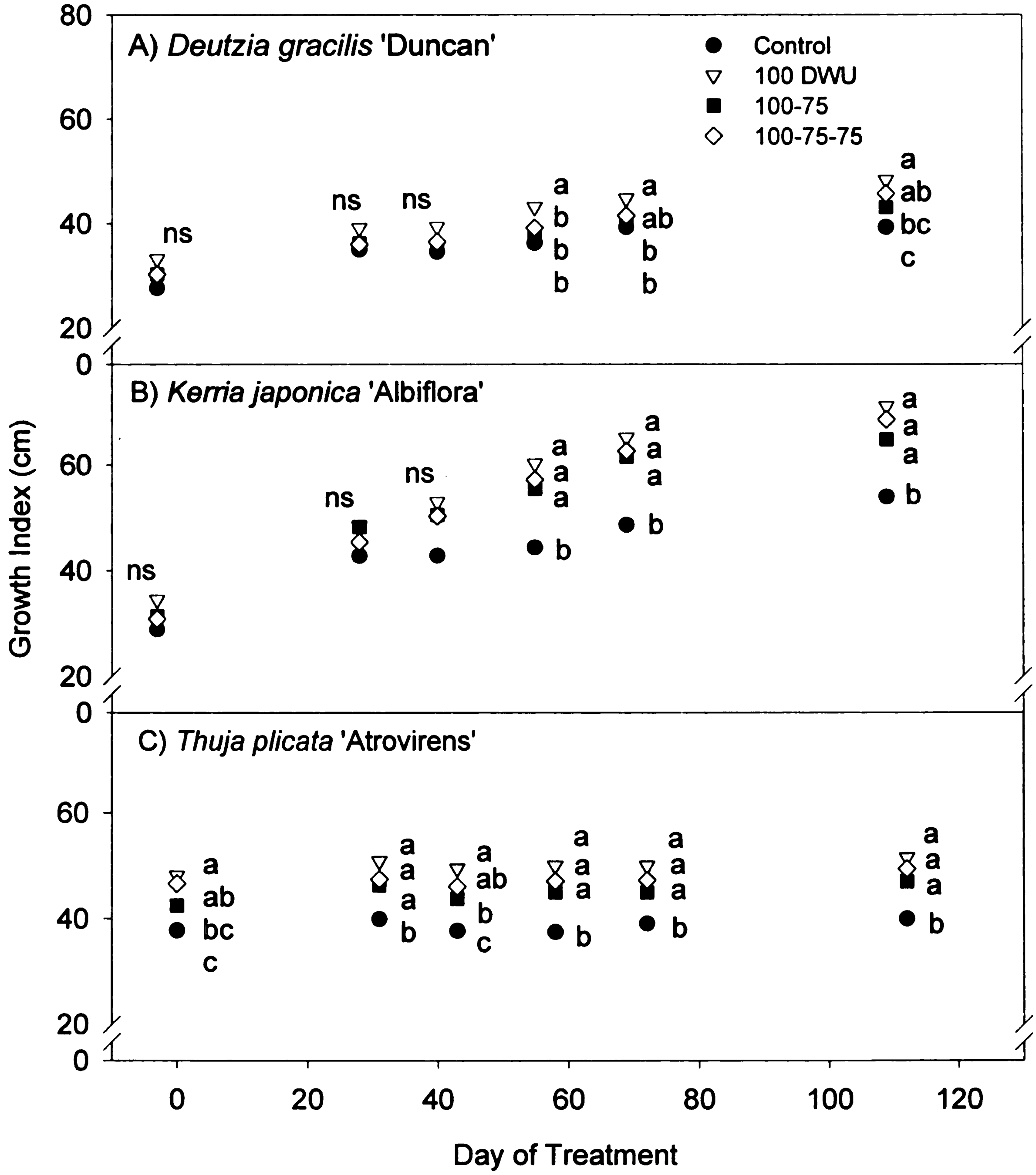

Figure 2.3. Growth index of three container-grown woody ornamentals under 4 irrigation treatments from 8 June to 30 September 2007. Day 0 = 13 June. Within each day treatments with the same letter are not significantly different (t-test, p = 0.05). ns = not significant. n = 18.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle with 100% DWU the first application followed by two applications of 75% DWU. DWU treatments applied at rate corresponding to species with the highest DWU.

Irrigation did not affect GI of *V. dentatum* 'Ralph Senior' in 2007 and final GI for the control, 100DWU, 100-75, and 100-75-75 treatments were 33 cm, 40 cm, 39 cm, and 39 cm, respectively. However, yellowing of foliage on plants in the control treatment was observed during both growing seasons for *V. dentatum* 'Ralph Senior' and during the 2007 runoff study for *K. japonica* 'Albiflora' and *T. plicata* 'Atrovirens', and may be due to nutrient deficiencies or water logging. After two seasons under the same irrigation treatments GI for most of the DWU treatments of *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', and *T. plicata* 'Atrovirens' were greater than control and for *V. dentatum* 'Ralph Senior' were not different than the control.

Improved growth of plants under DWU treatments compared to the control suggests that substrate water deficits did not become high enough to limit growth. Cameron et al. (2004) reported that shoot growth of *Cotinus coggygria* 'Royal Purple' and *Forsythia* x *intermedia* 'Lynwood' was reduced under deficit irrigation treatments of 80% potential evapotranspiration (ET_P) compared to plants irrigated at 150% ET_P after 8 weeks, and that stomatal conductance of *C. coggygria* 'Royal Purple' was reduced at 50% ET_P. In the current study total water applied by the control, 100DWU, 100-75, and 100-75-75 treatments was 123.0, 82.4, 72.3, and 68.9 $L \cdot container^{-1}$ compared to cumulative ET_P of 25.9 $L \cdot container^{-1}$. Our treatments were based on measured actual evapotranspiration (ET_A), not predicted daily ET_P and total water applied by all treatments was greater than 250% the cumulative ET_P during the experiment. Even though total water applied by the 100 DWU, 100-75 and 100-75-75 treatments was 33%, 41%, and 44% less than the control, final plant size of DWU treatments compared to the control indicate that water was not limiting. Additionally, because DWU irrigation volumes were applied at the rate corresponding to the species with the highest DWU on each measurement date, species with lower DWU did receive irrigation in excess of their DWU.

Other studies have also reported substantial reductions in irrigation with minimum effects on growth. Tyler et al. (1996) reported that a low leaching fraction (LF) of 0.0 to 0.2 reduced irrigation volumes by 44% with a reduction in top dry weight and total plant dry weight of 8% and 10%, compared to a high LF of 0.4 to 0.6 for *Cotoneaster dammeri* 'Skogholm'. Groves et al. (1998a) reported similar results with 90% of maximum top growth of *C. dammeri* 'Skogholm' and *Rudbeckia fulgida* 'Goldstrum' produced with up to a 40% reduction in irrigation volume. In the study by Groves et al. (1998a) 900 ml of irrigation was required daily for maximum growth of both species with reductions in growth of 24% to 35% with an irrigation volume of 200 ml. Welsh et al. (1991) reported that *Photina* × *fraseri* irrigated with 100%, 75%, and 50% replacements of actual water use did not differ in water use, shoot extension, shoot dry weight, leaf number, leaf area, or root area.

These studies document the adaptability of plants to grow at a wide range of irrigation volumes with minimal affects on growth. Water deficits required to reduce growth were unlikely in the current study as the most restrictive irrigation treatment was a three day cycle with one application at 100% DWU and two applications at 75% DWU. This is supported by final GI measurements of all species which under the three DWU treatments had GI greater than or equal to the control treatment.

Water Use Efficiency

To further investigate the effect of irrigation volume on growth response, water use efficiency (WUE) was estimated by calculating the increase in growth index per liter of water applied (irrigation plus precipitation) during the experiment, similar to the approach by Knox (1989). Water use efficiency values presented are estimates based on total water applied in each treatment and do not reflect differences in the DWU of plants in different treatments because DWU measurements used to schedule irrigation of all treatments were obtained from control plants only. In addition, losses from leaching, drift, and canopy shedding were not quantified. However, the WUE estimates presented provide valuable insight in explaining the growth response of plants under different irrigation volumes.

For *D. gracilis* 'Duncan' irrigation did not affect growth index increase but plants in the 100-75-75 treatment used water more efficiently than plants in the control treatment (Table 2.2). For *K. japonica* 'Albiflora' the increase in growth index of the control was lowest among treatments, and WUE of the control was lowest among treatments, while the WUE of the 100-75-75 treatment was higher than the 100DWU treatment. Increase in growth index of *T. plicata* 'Atrovirens' was not affected by irrigation volume, and WUE of the 100-75 treatment was higher than the control. For *V. dentatum* 'Ralph Senior' the increase in growth index of the 100-75-75 and 100-75 treatments were higher than the control and plants in the control had the lowest WUE among treatments. Our estimates of higher WUE under lower irrigation volumes agree with those of Tyler et al. (1996) who reported irrigation use efficiency of *Cotoneaster dammeri* 'Skogholm' under a low LF (0.0 to 0.2) was 29% greater than a high LF (0.4 to 0.6) and Groves et al. (1998b) who reported increasing irrigation efficiencies with decreasing irrigation volumes of *C. dammeri* 'Skogholm' and *Rudbeckia fulgida* 'Goldstrum'. The lower WUE of plants in the control treatment and measurements of DWU that were lower than control irrigation volumes show that irrigation applied to the control was in excess of plant needs. Excess irrigation applied to the control may have lead to the lower final GI of control plants of *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', and *T. plicata* 'Atrovirens' due to excess leaching of nutrients and decreased substrate aeration. Drew (1983) reported that near saturated conditions that limit substrate aeration can reduce root and shoot growth and reduce root respiration. Possible effects on growth due to excess leaching will be discussed with runoff data.

Table 2.2. Estimated water use efficiency (WUE) of 4 container-grown woody ornamentals under 4 irrigation regimes from 8 June to 30 September 2007. WUE estimated as increase in growth index (cm) per liter of water applied per container, including precipitation.

Taxa	Water use efficiency			
	Control[z]	100DWU	100-75	100-75-75
Total Water Applied[x]	137	96	86	83
Deutzia gracilis 'Duncan'				
Increase in GI (cm)	11.7 a[y]	15.1 a	12.8 a	15.4 a
WUE	0.09bB[w]	0.16abB	0.15abB	0.19aB
Kerria japonica 'Albiflora'				
Increase in GI (cm)	24.3 b	36.0 a	33.4 a	37.7 a
WUE	0.18cA	0.37bA	0.39abA	0.45aA
Thuja plicata 'Atrovirens'				
Increase in GI (cm)	2.2 a	3.4 a	4.5 a	2.8 a
WUE	0.02bC	0.04abC	0.05aC	0.03abC
Viburnum dentatum 'Ralph Senior'				
Increase in GI (cm)	1.6 b	8.1 ab	9.7 a	9.8 a
WUE	0.01bC	0.08aBC	0.11a BC	0.12aB

[z] Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle with 100% DWU the first application followed by two applications of 75% DWU. DWU treatments applied at rate corresponding to species with the highest DWU.

[y] Means with the same lowercase letters within the same row are not significantly different. Means separation with Tukey's test (α = 0.05).

[x] Liters·container^{-1} from 8 June to 30 September 2007.

[w] Means with the same uppercase letters within the same column are not significantly different. Means separation with Tukey's test (α = 0.05).

Electrical Conductivity and pH

Electrical conductivity values were highest in June for all treatments and species (Figure 2.4A – D). High EC levels also occurred in June for *Hydrangea arborescens* 'Dardom', *Spiraea fritschiana* 'Wilma', and *Viburnum* × *burkwoodii* 'Chenaultii' in an experiment that imposed the same irrigation treatments and was conducted during the same time period (Chapter 1). Following measurement in June, EC values of all treatments and species were within or slightly above the recommended range of 0.2 to 0.5 $dS \cdot m^{-1}$ (Yeager, et al., 1997) for pine bark substrates with treatment means ranging from 0.35 to 0.67 $dS \cdot m^{-1}$.

On day 15 leachate EC of the control and 100 DWU treatments were lower than the 100-75 treatment of *D. gracilis* 'Duncan' (Figure 2.4A). Leachate EC of the control and 100 DWU treatments were lower than the 100-75-75 treatment of *K. japonica* 'Albiflora' on day 15 (Figure 2.4B). There were no differences in leachate EC of *T. plicata* 'Atrovirens' (Figure 2.4C). On day 15 leachate EC of the control was lowest among treatments for *V. dentatum* 'Ralph Senior' (Figure 2.4D). There were no differences in leachate EC levels among treatments for any species on day 46 or 114 (Figure 2.4 A – D). A precipitation event of 35 mm occurred on day 83. On day 85 leachate EC of the control was highest among treatments for *D. gracilis* 'Duncan' and higher than the 100-75 and 100-75-75 treatments of *K. japonica* 'Albiflora' (Figure 2.4 A and B). Although differences in leachate EC of *D. gracilis* 'Duncan' and *K. japonica* 'Albiflora' occurred on day 85, soluble salt levels were above the recommended range. Differences among treatments in leachate EC levels on day 85 for *D.*

gracilis 'Duncan' and *K. japonica* 'Albiflora' closely resembled final GI measurements for these two species (Figure 2.3A and B; Figure 2.4A and B). Larger plant canopies in the DWU treatments compared to plants in the control were likely taking up greater quantities of nutrients resulting in lower leachate EC values in the DWU treatments compared to the control. Smaller plants in the control treatment possibly would be absorbing lower quantities of nutrients compared to plants in DWU treatments resulting in higher nutrient concentrations in the substrate solution. Additionally, higher irrigation volumes in the control treatment and more nutrients in the substrate solution would lead to greater nutrient leaching from containers. Lack of irrigation effect on leachate EC among treatments of *T. plicata* 'Atrovirens' during the entire experiment may be partly due to the small increase in GI that occurred during the study (Figure 2.3C and Figure 2.4C).

Bilderback et al. (1999) investigated whether weekly adjustments of irrigation volumes based on electrical conductivity could reduce excess and deficient nutrient levels in containers and lengthen controlled release fertilizer longevity. They reported EC of container-grown *Cotoneaster dammeri* 'Skogholm' in 3.8 L containers among all fertilization rates did not exceed the target concentration of 1.75 $dS{\cdot}m^{-1}$ required to increase the irrigation volume by 15% the following week and that EC levels were rarely above 0.5 $dS{\cdot}m^{-1}$ during the 152 day study. Like the current study precipitation was not excluded and Bilderback et al. (1999) concluded that periods of heavy rainfall negated the influence of irrigation volume on container EC. In climates where precipitation is frequent and sufficient enough to periodically leach excess salts from substrates EC is less likely to rise above recommended ranges. However, where this does not occur or during periods of drought EC should be more closely monitored to ensure soluble salts remain within acceptable ranges.

Irrigation did not affect leachate pH of any species or treatment during the experiment and leachate pH means for each species and treatment are shown in Figure AB1 for each measurement day. Leachate pH levels were higher than the recommended range of 5.0 to 6.0 for container-grown plants fertilized with controlled-release fertilizers (Yeager et al., 1997). Leachate pH values were likely affected by the alkalinity of irrigation water used. Treatment pH means of each species were pooled across all measurement days and means ± standard errors for *D. gracilis* 'Duncan', *K. japonica* 'Albiflora', *T. plicata* 'Atrovirens', and *V. dentatum* 'Ralph Senior' were 7.72 ± 0.05, 7.78 ± 0.05, 7.73 ± 0.04, and 7.60 ± 0.05.

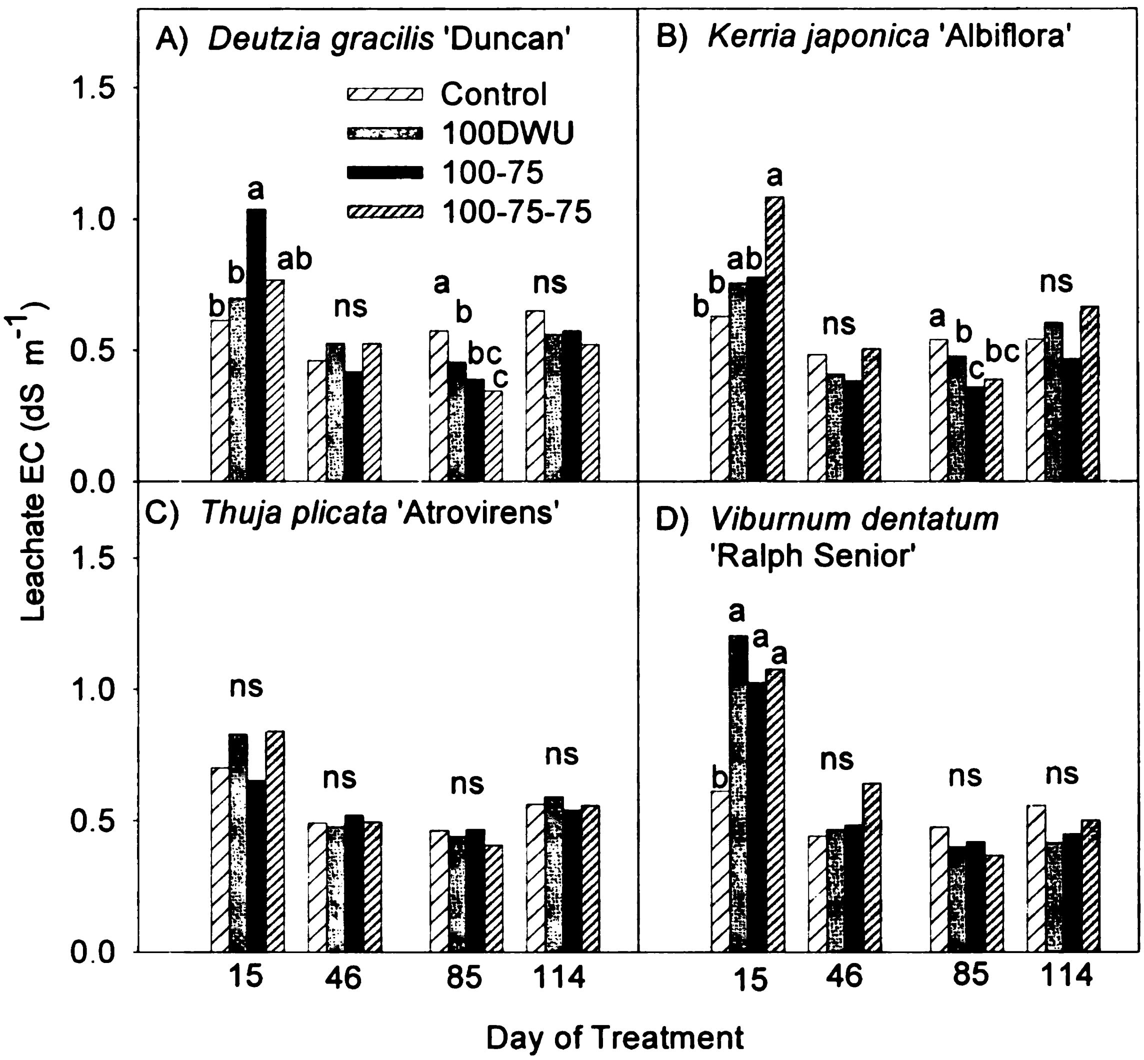

Figure 2.4. Leachate electrical conductivity (EC) of 4 container-grown woody ornamentals under 4 irrigation treatments applied from 8 June (Day 1) to 31 September (Day 115) 2007. Means separated by t-test (α = 0.05; n = 6). Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle with 100% DWU the first application followed by two applications of 75% DWU. DWU treatments applied at rate corresponding to species with the highest DWU.

Runoff Volume

Runoff, NO_3^--N, and PO_4^{3-}-P data were collected 2 days per month during the experiment. Because the 100-75 and 100-75-75 irrigation treatments consisted of multiple day cycles comparisons were made between the irrigation volumes applied on each collection day. On the first collection day each month the 100-75 and 100-75-75 treatments were on a day that received 75% DWU so runoff was collected for control, 100%DWU, and 75% DWU irrigation volumes. On the second day of collection all three DWU treatments received the 100% DWU volume so runoff from only control and 100% DWU irrigation volumes were collected.

Runoff volume from production areas irrigated with 100% DWU and 75% DWU irrigation volumes were lower compared to the control on each runoff collection day (Figure 2.5). Irrigation volumes applied at 100% and 75% DWU were 45% and 59% less than control irrigation volume across all measurement days. Runoff volume collected was extrapolated to a per hectare basis. Runoff volumes collected from the 100% DWU and 75% DWU irrigation volumes were lower than the control on each day of collection (Figure 2.5). Overall means of runoff volume collected for the experiment for the control, 100% DWU and 75% DWU irrigation volumes were 11.4×10^4 $L \cdot ha^{-1}$, 3.9×10^4 $L \cdot ha^{-1}$, and 2.4×10^4 $L \cdot ha^{-1}$, respectively. Percent irrigation captured as runoff for the control, 100% DWU, and 75% DWU irrigation volumes ranged from 31% to 74%, 14% to 63%, and 18% to 51%, respectively, depending on measurement day. Irrigation and runoff volumes were averaged over all measurement days and average percent irrigation captured as runoff for the control, 100% DWU, and 75% DWU irrigation volumes were 60%, 37%, and 32%, respectively. Lower percentages of irrigation captured as runoff from the 100% and 75% DWU irrigation volumes compared to the control likely resulted from substantially less water applied to containers receiving DWU irrigation volumes compared to the control. Additionally, lower pre-irrigation substrate moisture levels of containers receiving DWU irrigation volumes compared to the control likely allowed a higher percentage of applied water to be retained in the substrate.

The decreasing runoff associated with lower irrigation volumes in this study are consistent with those of Fare et al. (1994) who reported container leachate and total effluent were reduced by approximately 50% and 28% when 8 mm of irrigation was applied compared to 13 mm. Additionally, Karam and Niemiera (1994) developed regression models that showed leachate volume increased as pre-irrigation substrate water content (PSWC) increased and volume of water applied increased for continuous and cyclic overhead irrigation.

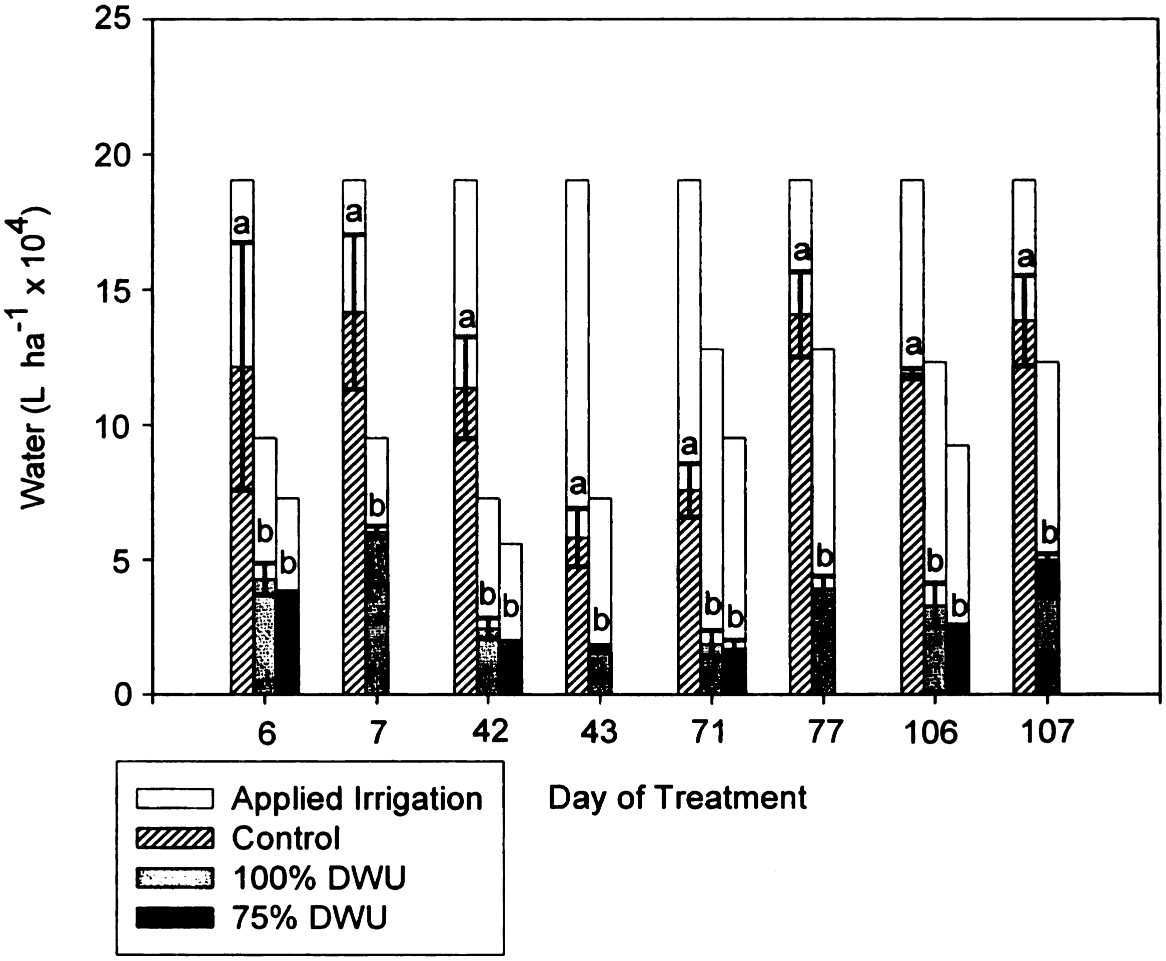

Figure 2.5. Daily Irrigation applied (L) and collected runoff (L) from 3 m x 6 m production areas (extrapolated to L·ha^{-1}) for 10.2 L container-grown woody ornamentals receiving a control irrigation of 19.05 x 10^{4} L·ha^{-1}·application^{-1}, 100% daily water use (DWU)·application^{-1}, or 75% DWU·application^{-1} from 8 June (day 1) to 30 September (day 115) 2007. On days with only control and 100%DWU bars, all production areas receiving irrigation as a percentage of DWU received 100% DWU. Error bars represent standard error of treatment means. Means separation within each day by Tukey's Test (α = 0.05).

Nitrates and Phosphates

Average concentrations of NO_3^--N in runoff did not exceed 5 mg·L^{-1} on any sample day for any treatment (Figure 2.6A). Runoff NO_3^--N concentration of the control and 100% DWU volumes were highest on day 7 at 4.13 mg·L^{-1} and 2.86 mg·L^{-1} (Figure 2.6A). Runoff from the 75% DWU irrigation volume was not collected on day 7 because all DWU treatments received 100%DWU. NO_3^--N concentration of the 75% DWU volume was highest on day 6 at 3.45 mg·L^{-1}. On day 71 NO_3^--N concentrations in runoff from the 75% DWU volume were greater than concentrations of the control and 100% DWU volumes (Figure 2.6A). On day 77 NO_3^--N concentrations from the 100% DWU irrigation volume were greater than the control.

Quantities of NO_3^--N and PO_4^{3-}-P recovered in runoff were calculated by multiplying concentration (mg·L^{-1}) by volume of runoff collected (L) and extrapolated to a per hectare basis. Quantities of NO_3^--N collected in runoff were greatest on day 7 for the control and 100% DWU irrigation volumes with means of 394 g·ha^{-1} and 253 g·ha^{-1} (Figure 2.6B). The 75% DWU irrigation volume was not sampled on this date. The day of greatest NO_3^--N collection of the 75% DWU treatment volume was day 6 with mean NO_3^--N of 128 g·ha^{-1}. Total applied N was 137 kg·ha^{-1}. Therefore NO_3^--N losses on day 7 for the control and 100% DWU irrigation volume and on day 6 for the 75% irrigation volume were 0.3%, 0.2%, and 0.1% of total applied N, respectively. Lower quantities of NO_3^--N were present in runoff from areas irrigated with the 100%

DWU volume on days 71, 77, and 107 compared to the control (Figure 2.6B). On day 6 lower quantities of NO_3^--N were present in runoff from areas irrigated with the 75% DWU volume compared to the control. Over all collection days the 100% DWU and 75% DWU irrigation volumes reduced runoff NO_3^--N quantities by an average of 38% and 59%. So although concentrations of NO_3^--N in runoff water may be higher from lower irrigation volumes total NO_3^--N quantity lost is lower because of greater runoff volume.

Daily mean concentrations of PO_4^{3-}-P in runoff did not exceed 1 $mg \cdot L^{-1}$ (Figure 2.7A). Peak PO_4^{3-}-P concentration in runoff coincided with dates of highest NO_3^--N concentration. Runoff PO_4^{3-}-P concentration of the control and 100% DWU irrigation volumes were highest on day 7 at 0.70 $mg \cdot L^{-1}$ and 0.78 $mg \cdot L^{-1}$(Figure 2.7A). The highest runoff PO_4^{3-}-P concentration of the 75% DWU irrigation volume was 0.52 $mg \cdot L^{-1}$ on day 6. On days 77 and 107 PO_4^{3-}-P concentrations in runoff from areas irrigated with the 100% DWU volume were greater than the control, 75% DWU volume was not collected on these days. On day 106 PO_4^{3-}-P concentration was greater in runoff collected from areas irrigated with 75% DWU compared to the control.

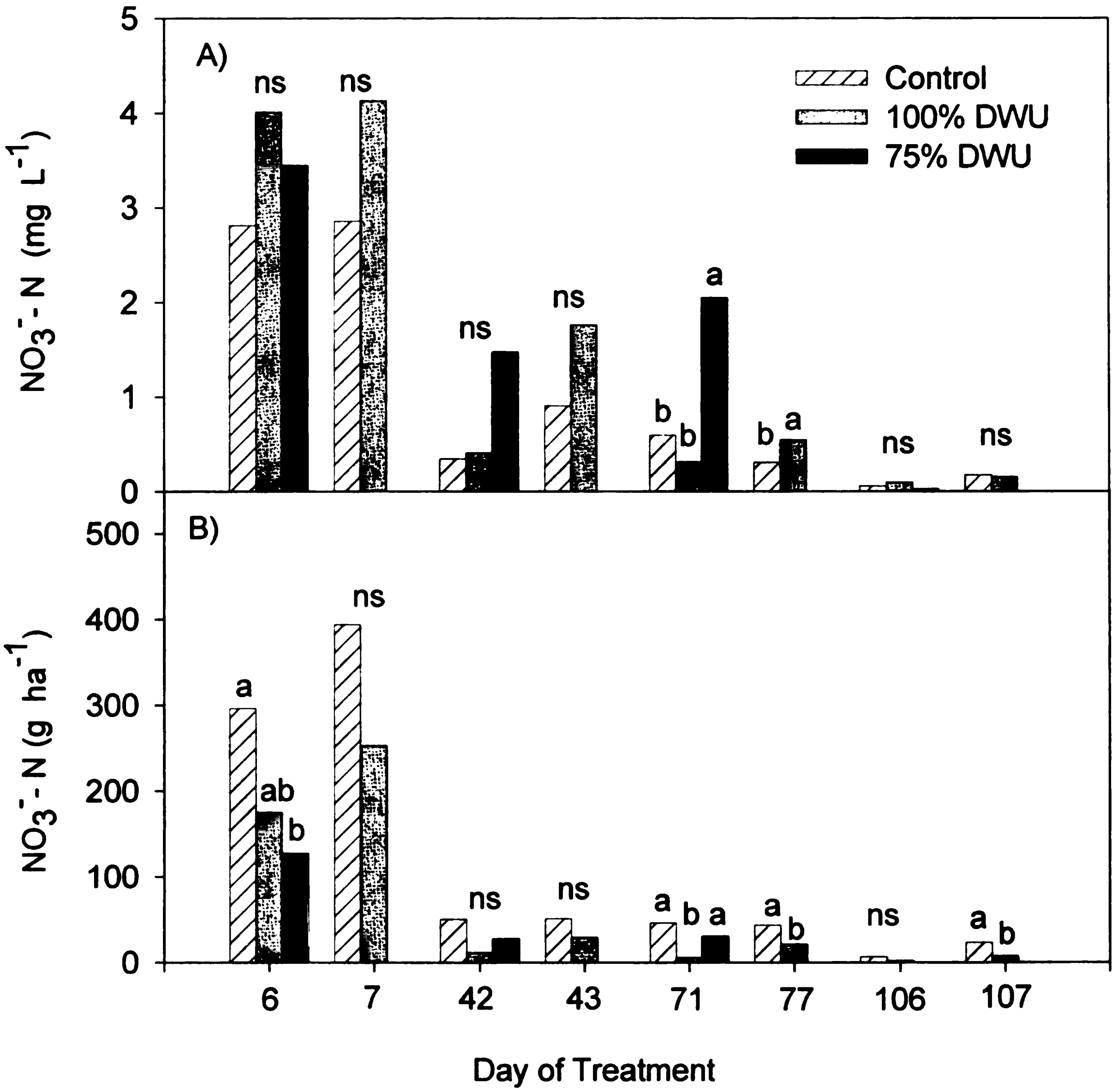

Figure 2.6. NO_3^- - N concentration (A) and NO_3^- - N quantity (B) in runoff from 3 m x 6 m production areas receiving irrigation as a control (19 mm-ha·application^{-1}), 100% daily water use (DWU)·application^{-1}, or 75% DWU)·application^{-1}. Day 1 = 8 June 2007. NO_3^- - N quantity expressed as g·ha^{-1} (B). On days 7, 43, 77, and 107 all DWU beds received 100% DWU. Means separation by Tukey's Test (α = 0.05).

Irrigating according to 100% DWU and 75% DWU resulted in lower quantities of PO_4^{3-}-P in runoff compared to the control on day 6 (Figure 2.7B).

Additionally runoff PO_4^{3-}-P quantity from the 100% DWU irrigation volume was lower compared to the control on day 7. Similar to NO_3^--N quantities, PO_4^{3-}-P quantities in runoff from the control and 100% DWU irrigation volumes were highest on day 7 with means of 90 $g \cdot ha^{-1}$ and 47 $g \cdot ha^{-1}$(Figure 2.7B). Quantity of PO_4^{3-}-P in runoff of the 75% DWU irrigation volume were highest at 19 $g \cdot ha^{-1}$, and occurred on day 6, the same day as peak NO_3^--N quantities were recovered from the 75% DWU volume. Total P applied was 16.8 kg ha^{-1}. Therefore PO_4^{3-}-P losses in runoff on day 7 for the control and 100% DWU irrigation volume and on day 6 for the 75% irrigation volume were 0.5%, 0.3%, and 0.1% of total applied P, respectively. Irrigating at volumes corresponding to 100% DWU and 75% DWU reduced PO_4^{3-}-P quantities in runoff by an average of 46% and 74% compared to the control over all collection days. When runoff PO_4^{3-}-P concentrations were higher for the 100% and 75% irrigation volumes there was no difference in quantity of PO_4^{3-}-P lost (Figure 2.7A and B). On days 6 and 7 there was no difference in runoff PO_4^{3-}-P concentration among irrigation volumes but PO_4^{3-}-P quantities in runoff were greater in the control compared to the 100% and 75% irrigation volumes (Figure 2.7A and B). The greater losses of PO_4^{3-}-P from the control treatment were due to the larger runoff volumes collected from the control production areas compared to the 100% and 75% irrigation volumes (Figure 2.5).

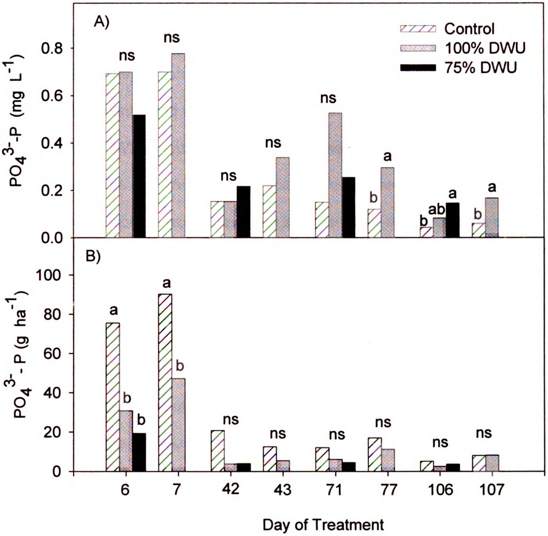

Figure 2.7. PO_4^{3-}- P concentration (A) and PO_4^{3-}- P quantity (B) in runoff from 3 m x 6 m production areas receiving irrigation as a control (19 mm-ha·application^{-1}), 100% daily water use (DWU)·application^{-1}, or 75% DWU·application^{-1}. Day 1 = 8 June 2007. PO_4^{3-}- P quantity expressed as g·ha^{-1} (B). On days 7, 43, 77, and 107 all DWU beds received 100% DWU. Means separation by Tukey's Test (α = 0.05).

Karam and Niemiera (1994) reported that leachate N (NO_3^--N and NH_4-N) concentration increased as pre-irrigation substrate water content (PSWC) decreased. Although PSWC was not measured on collection dates during the current study, volumes applied according to 100% DWU and 75% DWU were lower than the control treatment on each collection day and irrigation treatments based on DWU conserved water during the experiment make it likely that PSWC was lower in the DWU treatments. Assuming lower PSWC in containers receiving the 100% and 75% irrigation volumes compared to the control, containers in the control would have had lower nutrient concentrations due to greater dilution by higher volumes of water in the container substrate. Additionally, if containers receiving 100% and 75% irrigation volumes experienced less leaching than the control treatments more nutrients would remain in container solution increasing the concentration compared to the control. Larger canopies of measured plants in the experiment, and possibly guard plants, in the 3 DWU treatments compared to the control would have likely taken up more nutrients, leaving lower amounts of nutrients in the container to be leached. This would explain the differences in runoff NO_3^--N and PO_4^{3-}-P concentrations that occurred in our study. However, differences in NO_3^--N and PO_4^{3-}-P concentrations only occurred on 2 and 3 days out of 8 measurement days.

Rathier and Frink (1989) reported an average of 24% applied N was recovered in effluent, and that container nurseries can lose as much as

3367 $m^3 \cdot ha^{-1}$ in effluent and 139.4 $kg \cdot ha^{-1}$ NO_3^--N out of 484 $kg \cdot ha^{-1}$ total applied N when using overhead irrigation and slow release fertilizers. Fare (1993) reported 46% of applied N was lost as NO_3^--N in effluent. Phosphorus losses from container substrates of 8% to 27% were reported by Warren et al. (1995). Total losses of NO_3^--N from the current study were likely lower than those reported by Rathier and Frink (1989), and may have been higher had the fertilization date coincided with irrigation treatment initiation. Fertilizer was applied on 14 May, 25 days before irrigation treatments were initiated on 8 June. However, it is unlikely that NO_3^--N losses would have risen to levels reported by Rathier and Frink (1989) and Fare (1993) given the extra 25 days, because nutrient release of the controlled release fertilizer (Polyon Reactive Layers Coating) is temperature dependent and total N applied in the study was nearly 4 times less than that applied by Rathier and Frink (1989). Nutrient losses of recently transplanted material may also be higher than values reported here under the same irrigation treatments because it was the second growing season in the same containers for plants used in our study and roots would be expected to have fully exploited container substrate allowing for greater nutrient uptake upon release from the CRF. The highest daily losses of NO_3^--N and PO_4^{3-}-P occurred on 13 and 14 June (days 6 and 7) followed by a substantial decline in quantities collected on subsequent dates. This could have been due to increasing uptake of available nutrients as plant size and metabolic demand increased throughout the growing season.

Higher irrigation volumes resulted in greater losses of NO_3^--N and PO_4^{3-}-P, because of increased leaching. Several studies have documented an increase in container leachate and nutrient loss with an increase in irrigation volume. Karam and Niemiera (1994) reported that leachate volumes under a water application rate (WAR) of 2.1 $cm \cdot hr^{-1}$ resulted in 66% higher total N (NO_3^--N and NH_4-N) leached compared to a lower WAR of 0.7 cm/hr. While the study by Karam and Niemiera (1994) can not be directly compared with the current study because irrigation volume varied among treatments in our study, not WAR, it does document an increase in nutrient loss with an increase in leachate. Tyler et al. (1996) reported that a low leaching fraction (LF) of 0.0 to 0.2 reduced irrigation volume and effluent volume by 44% and 63% compared to a high LF of 0.4 to 0.6, and that after 100 days cumulative losses of NO_3^--N, and P in effluent were 66% and 57% lower from the low LF compared to the high LF. Additionally, Fare et al. (1994) reported total effluent was reduced by 51% with a 6 mm irrigation depth compared to 13 mm. With 13 mm irrigation and a high fertilizer rate 63% of the total N applied was leached as NO_3^--N, and this amount was reduced by 53% with 6 mm irrigation. Under the low fertilizer rate and 13 mm irrigation as much as 69% of total applied N was leached as NO_3^--N, and this amount was reduced by 64% with the 6 mm irrigation. Data from these studies showed that NO_3^--N losses increased with irrigation volume and container leaching, and support the greater NO_3^--N losses that occurred in the current study under higher irrigation and runoff volumes.

Plants in the control treatment of *K. japonica* 'Albiflora', *T. plicata* 'Atrovirens', and *V. dentatum* 'Ralph Senior' were chlorotic by the end of the experiment. Yellowing, exhibited by these plants could be from a combination of factors including: nutrient loss from leaching and low substrate aeration from excess water. However, a foliar analysis was not performed and therefore nutrient deficiencies could not be confirmed.

Conclusions

Total irrigation applied by the 100 DWU, 100-75 and 100-75-75 treatments was 33%, 41%, and 44% less than the control irrigation depth of 19 mm-ha·application^{-1} (1.07 L·container^{-1}·application^{-1}) during the 115 day experiment. Over 115 days from 8 June through 30 September soluble salts did not exceed the recommended levels in containers of any irrigation treatment despite an extended dry period from day 21 to day 58 (28 June to 4 Aug) in which only 12.45 mm of precipitation occurred and the largest precipitation event was 3.56 mm on day 46 (23 July; Figure 2.1). Final plant size under the 3 DWU treatments was greater than or equal to the size of control plants, depending on species.

Within each treatment *K. japonica* 'Albiflora' used water the most efficiently compared to the other three species (Table 2.2). In the control treatment *T. plicata* 'Atrovirens' and *V. dentatum* 'Ralph Senior' were the least efficient water users among the four species. *T. plicata* 'Atrovirens' consistently had the lowest WUE among species and the least variability among treatments. Average DWU data (Figure 2.2) and WUE data (Table 2.2) of the current study along with that of Knox (1989) shows that water use is influenced by species and seasonal growth pattern. Knowing the WUE of container-grown woody ornamentals would allow growers to more efficiently manage water resources even when scheduling irrigation applications based on DWU. For example, during a prolonged drought or in areas where water use restrictions are high or water is in low supply a grower could choose to grow species with high WUE in order to use irrigation more effectively. Based only on water use and efficiency, *K. japonica* 'Albiflora' would be a good choice to produce because it had the highest WUE of species in this study over all irrigation treatments, and a larger increase in GI and a higher final growth index under lower irrigation treatments.

In addition to conserving water irrigating according to DWU resulted in reduced runoff and nutrient leaching. Irrigation applications at 100% and 75% DWU volumes resulted in less captured runoff on every day of collection compared to the control. Overall leaching of NO_3^--N and PO_4^{3-}- P quantities were lower under the 100% and 75% DWU volumes compared to the control. Our research suggests that reduced leaching from lower irrigation volume reduces nutrient losses and may lead to increased plant growth by keeping greater quantities of nutrients in the substrate solution for plant absorption. By scheduling irrigation according to DWU growers can not only conserve water but reduce runoff and NO_3^--N, and PO_4^{3-}-P losses from containers.

Literature Cited

Anonymous. 1999. ThetaProbe soil moisture sensor. User Manual ML2-UM-1.21. Delta-T Devices Ltd. Cambridge, England.

Beeson, Jr., R.C., M.A. Arnold, T.E. Bilderback, B. Bolusky, S. Chandler, H.M. Gramling, J.D. Lea-Cox, J.R. Harris, P.J. Klinger, H.M. Mathers, J.M. Ruter, and T.H. Yeager. 2004. Strategic vision of container nursery irrigation in the next ten years. J. Environ. Hort. 22(2):113 – 115.

Bilderback, T.E., S.L. Warren, and J.H. Daniels. 1999. Managing irrigation by electrical conductivity. Proc. Int. Sym. Growing Media and Hydroponics. Acta Hort 481, ISHS 1999. 403 – 408.

Cameron, R.W.F., S. Wilkinson, W.J. Davies, R.S. Harrison-Murray, D. Dunstan, and C. Burgess. 2004. Regulation of plant growth in container-grown ornamentals through the use of controlled irrigation. Acta Hort. 630:305 – 312.

Dole, J.M., J.C. Cole, and S.L. von Broembsen. 1994. Growth of poinsettias, nutrient leaching, and water-use efficiency respond to irrigation methods. HortScience 29(8):858 – 864.

Drew, M.C. 1983. Plant injury and adaptation to oxygen deficiency in the root environment: a review. Plant and Soil 75:179 – 199.

Fain, G.B., C.H. Gilliam, K.M. Tilt, J.W. Olive, and B. Wallace. 2000. Survey of best management practices in container production nurseries. J. Environ. Hort. 18(3):142 – 144.

Fare, D.C. 1993. The influence of irrigation practices on nitrate-nitrogen leached from container-grown ornamentals. Ph.D. Dissertation. Auburn University, Auburn, AL.

Fare, D.C., C.H. Gilliam, G.J. Keever, and J.W. Olive. 1994. Cyclic irrigation reduces container nitrate-nitrogen concentration. HortScience. 29(12):1514 – 1517.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998 a. Irrigation volume, application, and controlled-release fertilizers: I. Effect on plant growth and mineral nutrient content in containerized plant production. J. Environ. Hort. 16(3):176 – 181.

Groves, K.M., S.L. Warren, and T.E. Bilderback. 1998 b. Irrigation volume, application, and controlled-release fertilizer II. Effect on substrate solution nutrient concentration and water efficiency in containerized plant production. J. Environ. Hort. 16(3):182 – 188.

Karam, N.S., and A.X. Niemiera,. 1994. Cyclic sprinkler irrigation and pre-irrigation substrate water content affect water and N leaching from containers. J. Environ. Hort. 12(4):198 – 202.

Knox, G.W. 1989. Water use and average growth index of five species of container grown woody landscape plants. J. Environ. Hort. 7(4):136 – 139.

Rathier, T.M. and C.R. Frink. 1989. Nitrate in runoff water from container-grown juniper and Alberta spruce under different irrigation and N fertilization regimes. J. Environ. Hort. 11:75 - 35.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. J. Environ. Hort. 14(4):199 - 204.

Warren, S.L., T.E. Bilderback, and H.H. Tyler. 1995. Efficacy of three nitrogen and phosphorous sources in container-grown azalea production. J. Environ. Hort. 13:147 – 151.

Weatherspoon, D.M. and C.C. Harrell. 1980. Evaluation of drip irrigation for container production of woody landscape plants. HortScience. 15(4):488 – 489.

Welsh, D.F., J.M. Zajicek, C.G. Lyons, Jr. 1991. Effect of seasons and irrigation regimes on plant growth and water-use of container-grown *Photina x fraseri*. J. Environ. Hort. 9(2):79 – 82.

Yeager, T.H. 2003. Implementation guide for container-grown plant interim Measure. EDIS Document ENH-895. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage: http://edis.ifas.ufl.edu/EP152 Accessed 01/23/2008.

Yeager, T. and G. Cashion. 1993. Controlled-release fertilizers affect nitrate nitrogen runoff from container plants. HortTechnology 3(2): 174 – 177.

Yeager, T., C. Gilliam, T. Bilderback, D. Fare, K. Tilt, and A. Niemiera. 1997. Best management practices guide for producing container-grown plants. Southern Nursery Association, 1000 Johnson Ferry Road, Suite E – 130, Marietta, GA 30068 – 2100.

CHAPTER THREE

DEVELOPING EVAPOTRANSPIRATION BASED MODELS TO ESTIMATE THE RELATIONSHIP BETWEEN GROWTH AND IRRIGATION OF *Spiraea fritschiana* 'Wilma' UNDER FOUR IRRIGATION REGIMES

DEVELOPING EVAPOTRANSPIRATION BASED MODELS TO ESTIMATE THE RELATIONSHIP BETWEEN GROWTH AND IRRIGATION OF *Spiraea fritschiana* 'Wilma' UNDER FOUR IRRIGATION REGIMES

Abstract

Difference in substrate volumetric moisture content 1 hr and 24 h after irrigation was used to calculate evapotranspiration (ET_A) of 10.2 L container-grown *Spiraea fritschiana* Schneid. 'Wilma' plants under 4 irrigation treatments. Irrigation treatments were 1. a control irrigation rate of 19 mm-ha applied per irrigation application; 2. irrigation scheduled to replace 100% daily water use per application (100DWU); 3. irrigation alternating every other application with 100% replacement of DWU and 75% DWU (100-75); and 4. an irrigation application replacing 100% DWU followed by two applications replacing 75% DWU (100-75-75). Irrigation applications were separated by at least 24 hours. Relationships of ET_A to reference potential evapotranspiration (ET_P) and growth index (GI) were investigated using regression analysis. ET_A was related to ET_P in all treatments. The best relationship for the control, 100DWU, 100-75, and 100-75-75 treatment included the independent variables ET_P, GI, and GI^2 (R^2 = 0.704); ET_P and GI (R^2 = 0.479); ET_P, GI, and GI^2 (R^2 = 0.438); and ET_P (R^2 = 0.424), respectively. Estimated crop coefficients (K_C) of the control, 100DWU, 100-75, and 100-75-75 treatments ranged from 1.7 to 3.5; 1.7 to 4.3; 2.0 to 5.4; and 1.6 to 6.7, respectively. Relationships of ET_A to ET_P and GI suggest that with further

research with more frequent GI measurements working models for scheduling irrigation are possible.

Introduction

Irrigation scheduling and water use are important issues facing the nursery industry as concerns about water use regulation, fresh water supplies, and runoff quality are forcing growers to develop water conserving irrigation programs. Irrigation scheduling is a process that determines 1. how much to irrigate and 2. when to irrigate (Warren and Bilderback, 2005). According to current best management practices (BMP's) irrigation applications should replace the amount of water lost since the last irrigation (Yeager et al., 1997). Plant daily water use (DWU) is the combined water loss from plant transpiration and substrate evaporation (Tyler et al., 1996; Yeager, 2003) and is a key component to efficient irrigation scheduling. However, scientific information regarding water requirements of woody ornamentals is limited.

Research on water use of agronomic crops using meteorological variables to estimate evapotranspiration has been conducted since the 1940's (Penman, 1948; Thornthwaite, 1944). Research by Thornthwaite (1944) resulted in the development of an equation for actual evapotranspiration:

$$ET_A = ET_P \times K_C$$

Where ET_A is actual evapotranspiration of the crop of interest, ET_P is potential evapotranspiration of a reference crop, and K_C is a crop specific crop coefficient.

However, factors unique to container production have presented considerable challenges when applying this research to estimate ET_A of container-grown crops. Unlike field crops, where one species is grown over a large area, container nurseries grow plants of different types, container sizes, and container spacings. Container-grown crops more closely resemble isolated stands of vegetation than field grown crops, and experience greater net radiation and advection resulting in higher K_C values due to increased ET_A (Doorenbos and Pruitt, 1975). Because of limited research on the water use of container-grown woody ornamentals the availability of K_C values for nursery crops is limited, making it difficult for growers to estimate ET_A (Irmak, 2005). Furthermore, determination of the variables required to derive crop K_C values can be expensive and estimating K_C values is time consuming because K_C are species specific (Beeson, 2005). Schuch and Burger (1997) reported that in high water use species K_C fluctuated seasonally from 1 to 4.7, likely due to differences in plant growth stage, location, and time of year, and that modifications to K_C values based on location and plant growth stage would be required when using K_C to estimate ET_A. For container crops calculation of ET_A must take into account the surface area available for water to enter the container substrate and can be calculated as follows (Schuch and Burger, 1997):

$$ET_A = \text{volume of water use } (cm^3) / \text{container surface area } (cm^2)$$

Multiplying this number by 10 coverts ET_A from cm to mm, which is the common unit of measurement for reporting ET_P.

Objectives

We examined diurnal patterns of substrate moisture content and temperature, and environmental weather data during a 128 day experiment. Our objectives were to 1. determine effects of irrigation treatment on substrate volumetric moisture content (SVMC) and substrate temperature and 2. develop predictive models that use estimated ET_P data and plant growth measurements to predict ET_A of container-grown *Spiraea fritschiana* Schneid. 'Wilma'. Of additional interest was the estimation of K_C values that were among the first for *S. fritschiana* 'Wilma'.

Materials and Methods

Site Specifications

The experiment was conducted at the Michigan State University Horticulture Teaching and Research Center (HTRC) in Holt, Michigan at latitude 42.67°, longitude -84.48°, at an elevation of 264 m. A Michigan Automated Weather Network (MAWN) weather station is located on-site at the HTRC. The current experiment was conducted as part of a related irrigation experiment. The concurrent study evaluated the effects of irrigation scheduling according to plant DWU on growth and water conservation for ten species of container-grown woody ornamentals compared to a control irrigation of 19 $mm\text{-}ha \cdot day^{-1}$ applied from 8 June through 13 October of 2007. The experiments were conducted on a site developed for outdoor nursery container plant production. The production surface consisted of limestone gravel covering a landscape fabric. Rainfall was recorded at the MAWN weather station located at the HTRC.

Plant Material and Culture

Spiraea fritschiana 'Wilma' was one of the 10 species grown in the concurrent experiment and chosen as the species for this experiment because spiraea are one of the most commonly used landscape plants. *Spiraea fritschiana* 'Wilma' is a pink flowering Korean spiraea with bluish-green leaves and yellow-orange fall color that is cold hardy to USDA Zone 4. Plants were received as liners in 5.7 cm plug cells from a commercial nursery and were transplanted into 10.2 L containers from 3 – 7 Sept. 2006. Container substrate consisted of 85% pine bark:15% peat moss (vol:vol). Plants were over-wintered in a hoop house covered with a single layer of white plastic. Plants were fertilized on 14 May 2007 with 26 g per container of a 19.0N–2.2P–7.5K controlled-release fertilizer with micronutrients (Harrell's Inc., Lakeland, FL). Plants were pruned to a uniform height on 21 May 2007. All cultural practices were kept identical except irrigation.

Irrigation Treatments

The experimental design for SVMC and substrate temperature measurements was a completely randomized design (CRD) with one factor, irrigation treatment with one plant as the experimental unit, and a CRD with subsamples for plant growth parameters in the concurrent study with 6 plants of each taxa in each treatment replicate. Plants received one of four irrigation treatments: 1. a control irrigation rate of 19mm-ha·application^{-1} (1.07 L·container^{-1}·application^{-1}); 2. irrigation scheduled to replace 100% DWU per application (100DWU); 3. alternating every other application with 100% DWU and 75% DWU (100-75); and 4. a three application cycle with one application of 100% DWU followed by two applications of 75% DWU (100-75-75). Irrigation treatments were separated by at least 24 h. Treatments were replicated 3 times and were applied from 8 June (day 1) to 13 Oct. (day 128) 2007.

In the concurrent study plants were grown on 4.9 m × 7.3 m production areas that served as one treatment replicate. There were six plants each of the 10 species per treatment replicate. The 60 plants per treatment replicate were randomly arranged in six rows of ten, spaced 45 cm on center within each treatment replicate. Within each treatment replicate of the concurrent study one of the six *S. fritschiana* 'Wilma' plants was randomly chosen for the current experiment and represented one treatment replicate. There were three replicates of each irrigation treatment. Containers were spaced 45 cm on center and each *S. fritschiana* 'Wilma' was surrounded by plants of different species used in the concurrent study.

Measuring DWU to Schedule Irrigation Applications

Daily water use for irrigation scheduling in the concurrent experiment was measured using a ThetaProbe Type ML2x soil moisture sensor (Delta-T Devices Ltd., Cambridge, U.K.) connected to a ThetaMeter Hand-Held Readout Unit Type HH1 (Delta-T Devices Ltd.). A substrate specific calibration was conducted to improve the accuracy of the ThetaProbe as outlined in the ThetaProbe Type ML2x user manual (Anonymous, 1999). The equation from the substrate specific calibration was used to convert ThetaProbe voltage to SVMC. Volumetric moisture content of the container substrate was measured 1 h after irrigation and prior to irrigation the following day during 24 h periods without precipitation. The percent difference in SVMC was multiplied by the average volume of container substrate (9.7 $L{\cdot}container^{-1}$) to determine the volume of water lost from the container. Irrigation scheduling for DWU treatments was based on DWU of the 3 control treatment replicates.

Irrigation Applications

Irrigation rate of the overhead system was determined by measuring the depth of water applied from 3 of the 12 irrigation zones. Irrigation rate was measured using eight rain gauges randomly placed within each replicate to collect water for 30 min. The irrigation cycle was repeated with the eight rain gauges randomized again for a total of 16 measurements per replicate. The average application rate for the 3 replicates was 0.434 $mm{\cdot}min^{-1}$. Irrigation applications were scheduled using a Rain Bird ESP-12LX Plus controller (Rain

Bird Corporation; Azusa/Glendora, CA). Irrigation applications for each treatment replicate were controlled by a 2.54 cm Rain Bird 13DE04K solenoid valve (Rain Bird Corporation). Irrigation was applied through 12 Toro 570 Shrub Spray Sprinklers (The Toro Company; Riverside, CA). Sprinklers were mounted on 1.3 cm diameter risers 66 cm high with 3.7 m throw distance diameter. Emitters were arranged in three rows of four, with four 90 degree emitters on the corners, six 180 degree emitters on the edges, and two 360 degree emitters in the middle of each replicate. All irrigation was directed into the block and emitters were spaced 3.67 m apart to allow 100% overlap with a distribution uniformity of approximately 80%.

Because water use of multiple species was evaluated in the concurrent study irrigation applied through the overhead irrigation system corresponded to the species with the lowest DWU on each measurement day. For species with a higher DWU additional water was applied by hand. Irrigation applications were scheduled to apply the correct volume based on irrigation rate and container surface area assuming 100% canopy penetration. The irrigation began between 0700 HR and 0900 HR. Irrigation time of the control replicates were the same throughout the experiment, but irrigation start time and duration of DWU treatments varied based on the time required to add 100% and 75% DWU volumes.

Measured Variables and Instrument Installation

Substrate volumetric moisture content was measured with a ThetaProbe Type ML2x (Delta-T Devices Ltd.) connected to a Campbell Scientific CR 3000 datalogger (Campbell Scientific, Inc., Logan, Utah) as a single channel analogue input with a 5 second warm-up time. ThetaProbe output was measured as a single ended voltage source and a substrate specific calibration equation was used to convert ThetaProbe output in volts to SVMC following downloading from the datalogger. Each ThetaProbe was inserted at a 20° angle as recommended by the ThetaProbe Soil Moisture Sensor User Manual ML2x-UM-1.22 (Anonymous, 1999) for in situ measurements taken during and after rainfall. Volumetric moisture content measurements were made in the top 60 mm from the substrate surface. The sensing array of rods of the ThetaProbe is comprised of a 60 mm long center rod with three additional 60 mm rods equally spaced from the center rod forming 30 mm diameter cylinder within which SVMC is measured. The center rod was inserted 60 mm from the north rim of the container. Container height was 245 mm. Substrate temperature was measured with a model 107-L water/soil temperature sensor (Campbell Scientific, Inc., Logan, Utah). One probe was used per container and was inserted 60 mm from the south rim of the container with each probe extending to a depth of 100 mm. One HMP45C-L Vaisala Temperature and Relative Humidity Probe (Campbell Scientific, Inc., Logan, Utah) enclosed in a solar radiation shield measured air temperature and relative humidity at a height of 1.5 m above the production site. Net radiation was measured at a height of 2.5 m above the production area using a net radiometer (Model Q7, Radiation and Energy Balance Systems, Inc., Seattle, WA). Measurements were taken once per minute with 15 minute averages recorded by a CR3000 data logger (Campbell Scientific, Inc., Logan, Utah). Daily maximums and minimums were also recorded. Meteorological data from the MAWN weather station at the HTRC was obtained at:

http://www.agweather.geo.msu.edu/mawn/

Data from the MAWN weather station is provided courtesy of the Michigan State University Agricultural Weather Office, Michigan State University State Climate Program, and the Enviro-weather Project.

Estimation of ET_P and Calculation of ET_A

Reference potential evapotranspiration (ET_P) data were obtained from the on-site MAWN weather station using the modified Penman method according to Kincaid and Heerman (1974). Actual evapotranspiration was calculated using automated data from the ThetaProbes connected to the datalogger. Actual evapotranspiration was calculated for the 12 days when DWU was measured to schedule irrigation applications in the concurrent study. Actual evapotranspiration was calculated as the difference in SVMC one hour after the maximum daily SVMC and the SVMC 24 hours later or from the 15 minute average prior to SVMC increase from the next irrigation, whichever occurred first. On days when two peaks in SVMC occurred, one from the overhead application and the second from hand watering, one hour after the second peak was used as the 1 hour measurement in ET_A calculation. The volume of water lost from a container during each day was converted to daily ET_A (mm·day^{-1}) by dividing the volume of water used in cubic centimeters by the surface area of the container in square centimeters and multiplying by 10.

Growth Index

Plant growth index (GI) was measured every 2 to 4 weeks during the experiment. Growth index was calculated by summing plant height from the container rim, plant width A, and the plant width perpendicular to plant width A and dividing by 3. Days on which ET_A was calculated for regression analysis did not coincide with days of GI measurement. Therefore plant GI on days when ET_A was calculated was estimated from the difference in GI from the GI measurement days that the day of ET_A measurement fell between. The change in GI was divided by the number of days between measurement dates to obtain a daily growth rate for that period. The daily growth rate was multiplied by the number of days after the initial GI measurement date that the DWU measurement date occurred. The additional estimated growth was added to the GI on the initial GI measurement date to give the GI of the plant on the DWU date.

Statistical Analysis

The three moisture sensors and temperature sensors in each treatment were evaluated for homogeneity among treatments by examining plots of 15 minute means among the three containers (each a treatment replicate) within each treatment by day and over the 128 days of the experiment. Next, daily means, daily maximums, and daily minimums of SVMC and substrate temperature from the three sensors in each treatment replicate were subjected to analysis of variance using PROC GLM of SAS Version 9.1 (SAS Institute, Inc., Cary, NC., USA) and when significant means were separated using Tukey's Honest Significance test ($\alpha = 0.05$).

Daily water applied, daily mean, daily maximum, and daily minimum SVMC and substrate temperature were analyzed for treatment effects by subjecting daily means, daily maximums, and daily minimums to ANOVA using PROC GLM of SAS Version 9.1 (SAS Institute, Inc.) and when significant means were separated using Tukey's Honest Significance test ($\alpha = 0.05$).

Linear regression for the relationship between the dependent variable ET_A and the independent variable ET_P was conducted using PROC REG of SAS Version 9.1 (SAS Institute, Inc.). Estimated GI was added to the model when significant at the 0.05 level and when an increase of ≥ 0.05 in the R^2 value resulted. When the model included a linear term for GI, a quadratic term was added to the model when significant at the 0.05 level and an increase of ≥ 0.05 in the R^2 value resulted.

Results and Discussion

Weather Conditions

Mean daily temperature during the experiment at the production area and the weather station were 20.6 °C and 19.7 °C (Table 3.1). Daily mean relative humidity was 70.6% and 71.4% at the production area and the weather station (Table 3.2). Daily maximum and mean wind speed measured at the weather station during the experiment are shown in Figure 3.3, and the mean daily wind speed was 1.8 $m \cdot s^{-1}$ (Table 3.1). Daily maximum solar radiation values were fairly steady during the first half of the experiment and then slowly declined (Figure 3.4). Mean daily reference potential evapotranspiration (ET_P) was 3.8 mm and maximum ET_P recorded was 7.2 mm on day 31 (8 July; Figure 3.5). Total cumulative ET_P during the 128 day experiment was 490.1 mm. Cumulative precipitation during the experiment measured at the weather station was 281.1 mm (Figure 3.6). The greatest precipitation event was 47 mm on day 74 (24 August; Figure 3.6).

For the period May though October 2007 average air temperature recorded at the MAWN weather station was 1.3°C higher than the 30 year average of 16.8°C for East Lansing, Michigan (Anonymous, 2008). Total precipitation during this period was 29.7 mm higher than the 30 year average of 465.1 mm. However, during the month of July only 12.5 mm of precipitation fell compared to the 30 year average of 75.7 mm. There was a water deficit during the period as cumulative reference potential evapotranspiration of 675.3 mm exceeded cumulative precipitation by 180.5 mm.

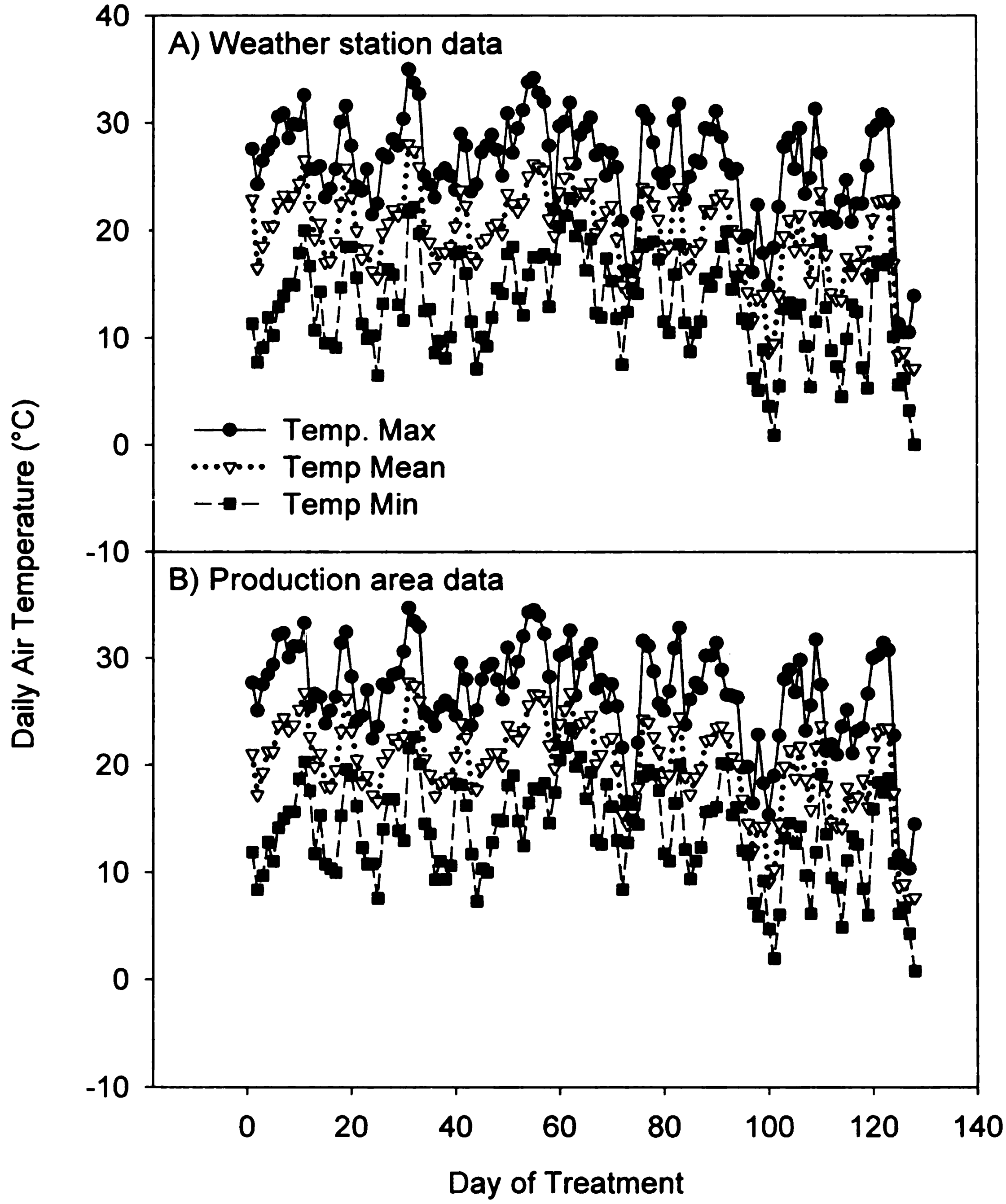

Figure 3.1. Daily maximum, mean, and minimum air temperature collected from A) a Michigan Automated Weather Network (MAWN) weather station located on-site at the Michigan State University Horticulture Teaching and Research Center and B) 1.5 m above the production area. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data from MAWN weather station courtesy of Michigan State University and the Enviro-weather Project.

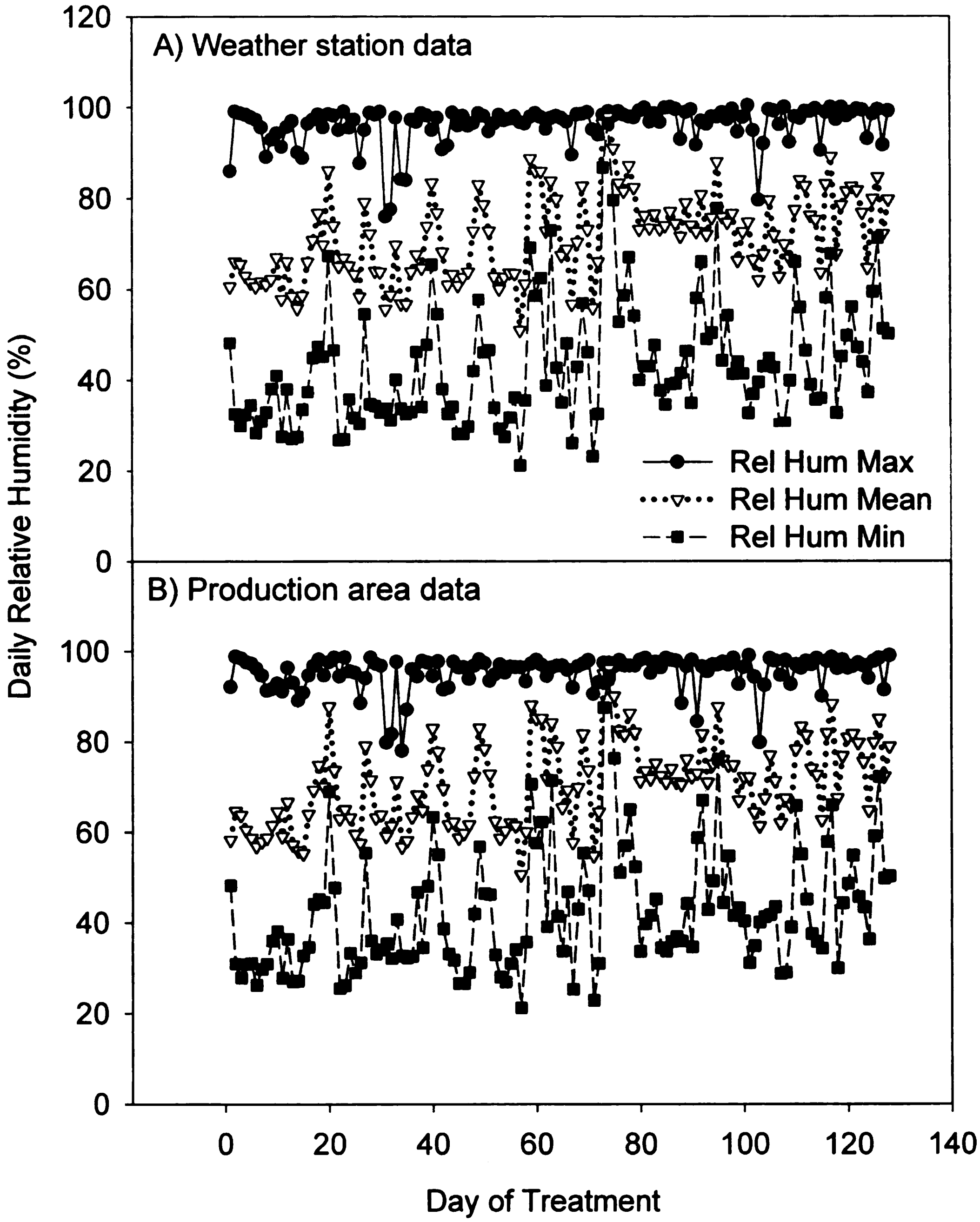

Figure 3.2. Daily maximum, mean, and minimum relative humidity collected from A) a Michigan Automated Weather Network (MAWN) weather station located on-site at the Michigan State University Horticulture Teaching and Research Center and B) 1.5 m above the experiment production area. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data from MAWN weather station courtesy of Michigan State University and the Enviro-weather Project.

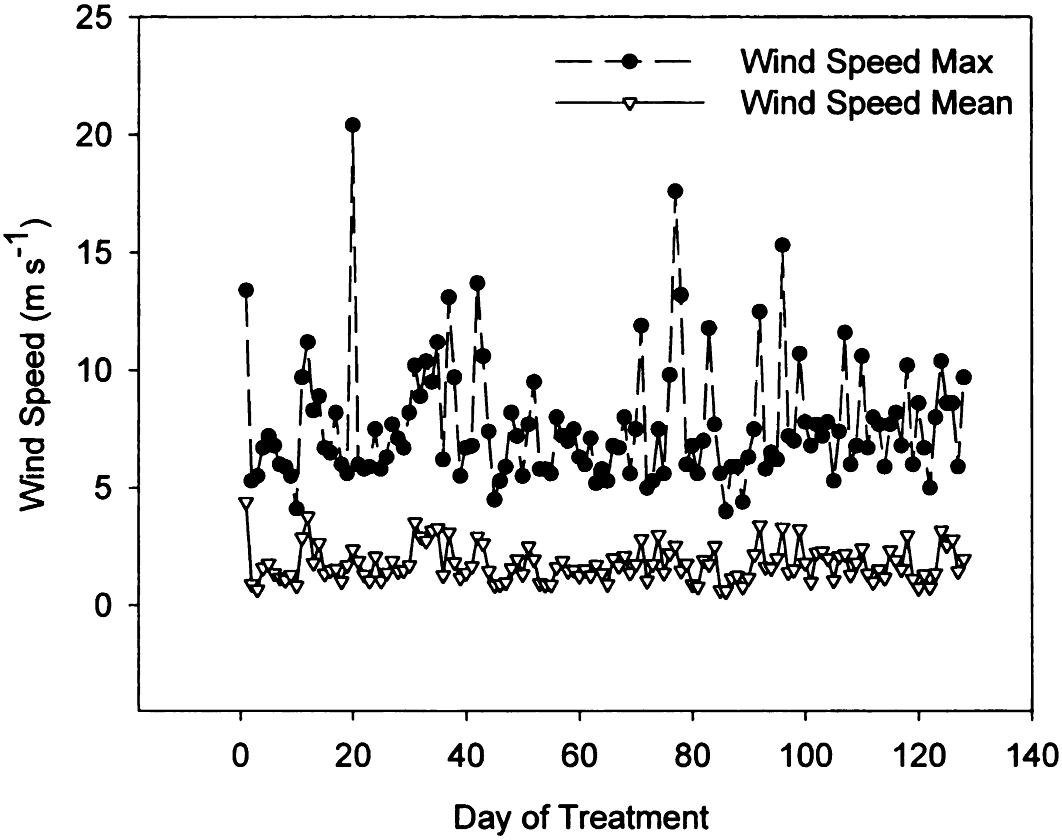

Figure 3.3. Daily maximum and mean wind speed measured at a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture Teaching and Research center. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data courtesy of Michigan State University and the Enviro-weather Project.

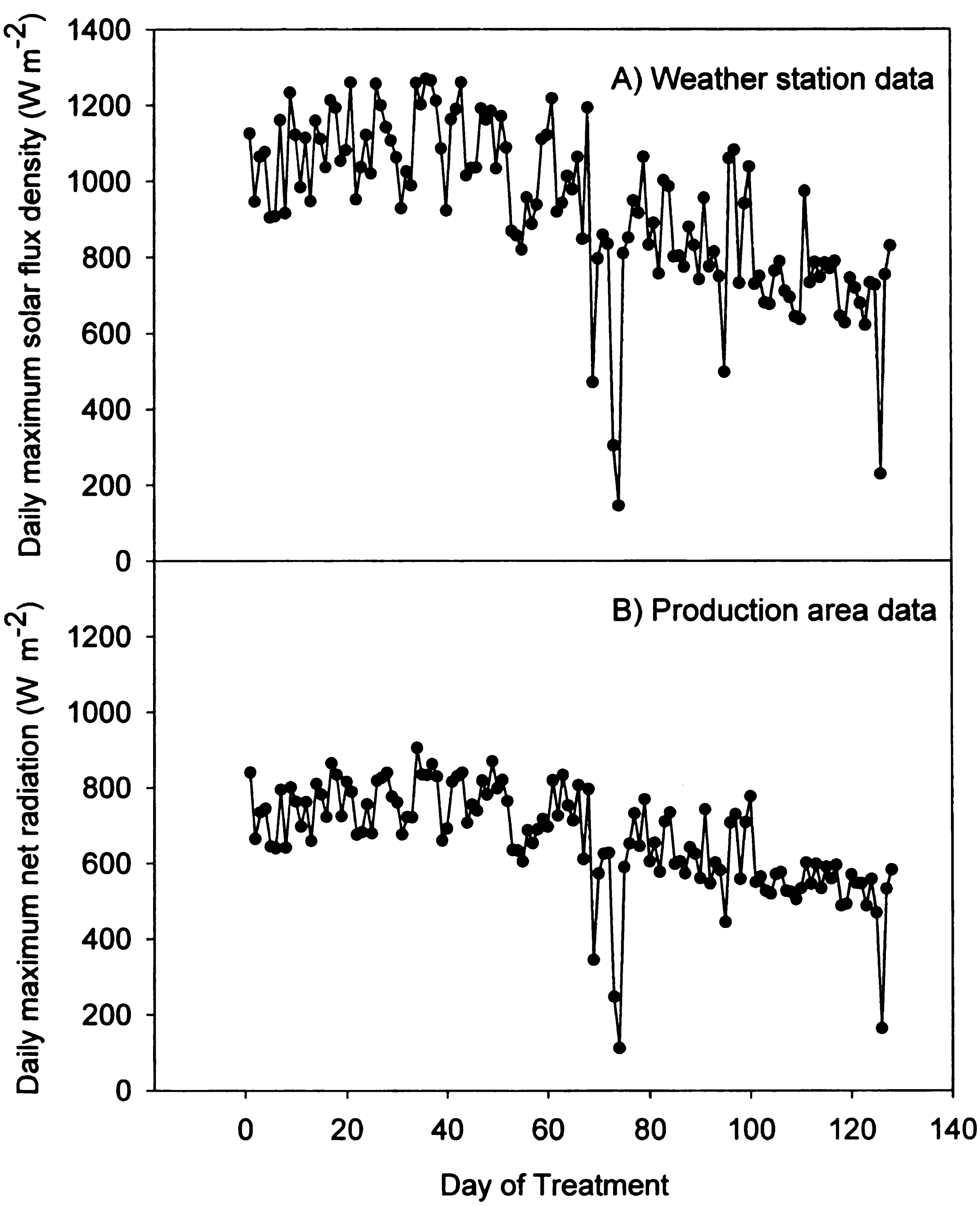

Figure 3.4. Daily maximum solar radiation collected from A) a Michigan Automated Weather Network (MAWN) weather station located on-site at the Michigan State University Horticulture Teaching and Research Center and B) from 2.5 m above the experiment production area. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data from MAWN weather station courtesy of Michigan State University and the Enviro-weather Project. Radiation values of A are higher compared to B because the sensor at A measures incoming radiation and sensor at B measures incoming and outgoing radiation and outputs the difference.

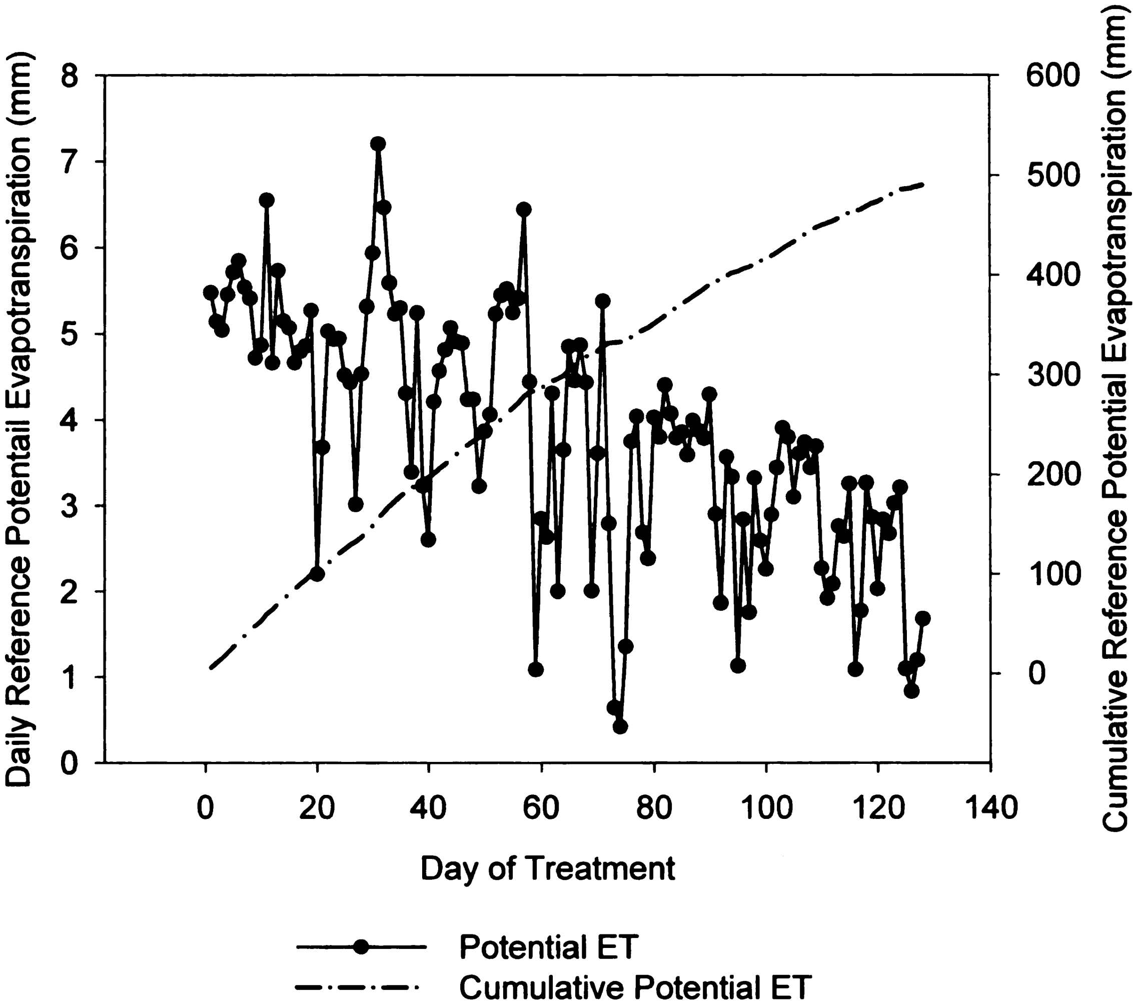

Figure 3.5. Daily reference potential evapotranspiration and cumulative reference potential evapotranspiration calculated using the modified Penman method. Data was collected from a Michigan Automated Weather Network (MAWN) weather station at the Michigan State University Horticulture Teaching and Research center. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data courtesy of Michigan State University and the Enviro-weather project.

Table 3.1. Weather variables measured at the production area and at a Michigan Automated Weather Network (MAWN) weather station located on-site at the Michigan State University Horticulture Teaching and Research Center (HTRC). Data reported are averaged over 8 June through 13 October 2007.

Variable	Location: Production Area	Location: Weather Station[z]
Air Temperature Max. (°C)	26.55	26.01
Air Temperature Mean (°C)	20.15	19.70
Air Temperature Min. (°C)	13.74	13.08
Relative Humidity Max. (%)	95.31	96.18
Relative Humidity Mean (%)	70.55	71.41
Relative Humidity Min. (%)	42.47	43.47
Wind Speed Mean ($m \cdot s^{-1}$)	N.A.	1.75
Net Radiation Max. ($W \cdot m^{-2}$)	666.45	N.A.
Net Radiation Mean ($W \cdot m^{-2}$)	138.91	N.A.
Net Radiation Min. ($W \cdot m^{-2}$)	-50.55	N.A.
Solar Flux Density Max. ($W \cdot m^{-2}$)	N.A.	18754.02
Solar Flux Density Total ($kJ \cdot m^{-2}$)	N.A.	928.91
Reference Potential Evapotranspiration ($mm \cdot d^{-1}$)	N.A.	3.83
Cumulative Reference Potential Evapotranspiration ($mm \cdot d^{-1}$)	N.A.	490.10
Cumulative Precipitation (mm)	N.A.	281.12

[z]Data measured at a MAWN weather station located on site at the HTRC. Data courtesy of Michigan State University and the Enviro-weather Project.

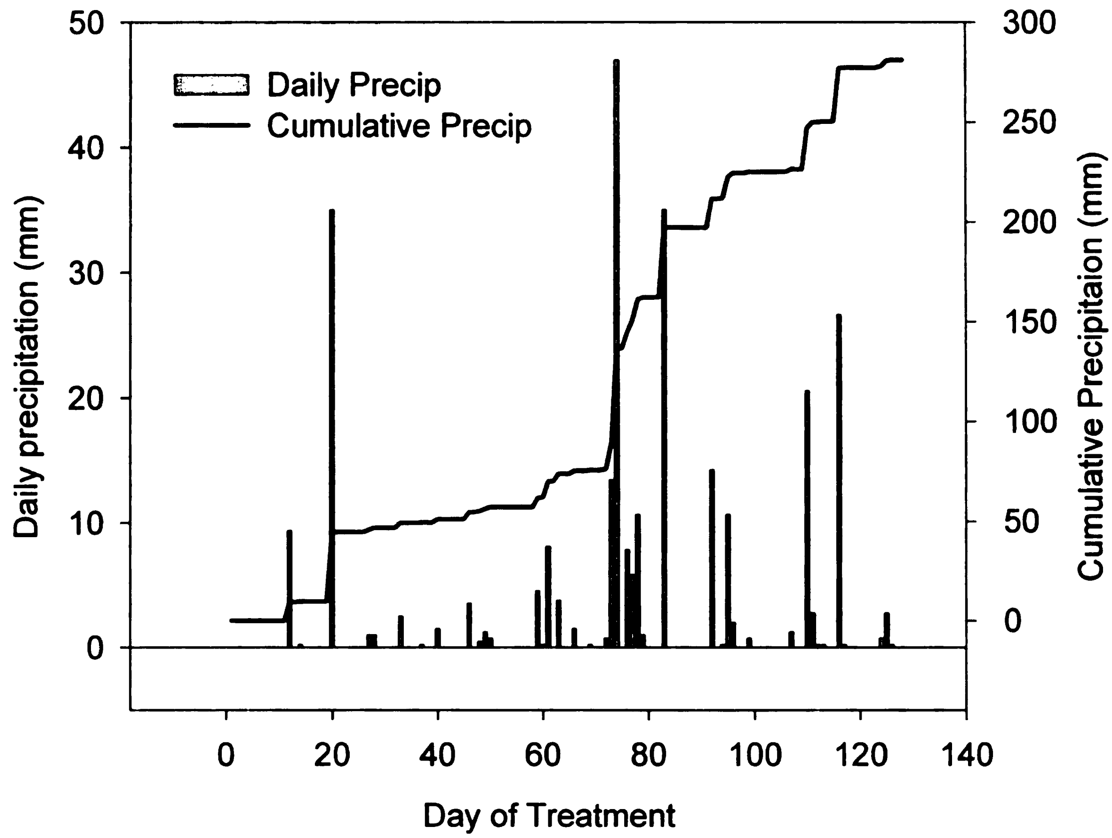

Figure 3.6. Daily precipitation (bars) and cumulative precipitation (line) measured from a Michigan Automated Weather Network (MAWN) weather station located on-site at the Michigan State University Horticulture Teaching and Research Center. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Data courtesy of Michigan State University and the Enviro-weather Project.

Substrate Volumetric Moisture Content

One way to measure DWU of container-grown plants is by analyzing differences in SVMC based on soil moisture sensor measurements (Cornejo et al., 2005; Garcia y Garcia et al., 2004). Many field and laboratory studies have shown that TDR and capacitance sensors accurately measure water content in a variety of soil types (Blonquist et al, 2005; Eller and Denoth, 1996; Hanson and Peters, 2000; Topp and Davies, 1985; and Yoder et al., 1998). One advantage of measuring the change in SVMC between irrigation events is that ET_A can be calculated and used to schedule irrigation without relying on other variables to estimate ET_A.

Because of substantial differences in SVMC compared to other reps in the same treatment, rep 1 of the control and rep 2 of the 100-75-75 treatments were excluded from further analysis (Table AB4 and Figure AB2). The lower SVMC in rep 1 of the control treatment compared to reps 2 and 3 could have resulted from any factor resulting in poor contact between the sensing rods of the ThetaProbe and the container substrate. Such factors include: air pockets, roots close to or pierced by rods (Anonymous, 1999), pieces or clumps of bark, or any other factor causing heterogeneity in the substrate. The higher daily mean SVMC of rep 2 compared to reps 1 and 3 in the 100-75-75 treatment could be the result of a plugged drain hole that restricted or prevented drainage.

Beginning around day 60 daily mean SVMC of all treatments increased as the experiment progressed (Figure 3.7B). Additional water applied by precipitation, which was more frequent during the second half of the experiment was one factor contributing to this increase. Another factor could be that roots were filling pore space so drainage was not as good as earlier in the growing season. Daily mean SVMC was highest in the control at 0.402 $m^3 \cdot m^{-3}$ and lowest in the 100-75-75 treatment at 0.296 $m^3 \cdot m^{-3}$ (Table 3.2). Even though mean daily SVMC of the 100-75-75 treatment was lower than the 100DWU and 100-75 treatments, the difference between the 3 DWU treatment means was

≤ 0.022 $m^3 \cdot m^{-3}$ (Table 3.2). The decrease in SVMC in DWU treatments from day 0 to day 13 was likely caused by an increase in water use after the first DWU measurement date (Figure 3.7). Canopy coverage at this time was also the lowest during the experiment and together with long day length resulted in some of the highest maximum substrate temperatures during the experiment. The following increase in SVMC was likely caused by the precipitation event of 9.4 mm on day 12 and an irrigation scheduling update from DWU measurements on day 13 (Figure 3.6).

Total water applied (including precipitation) to the control, 100DWU, 100-75, and 100-75-75 treatments were 153.0, 114.4, 102.2, and 98.0 $L \cdot container^{-1}$, respectively (Table 3.3). Higher average daily irrigation amounts and total water applied resulted in daily maximum, mean, and minimum SVMC that were highest in the control and lowest in the 100-75-75 treatment (Table 3.2). Water applied to substrates at higher SVMC's, such as the control, would leach from the container before substrates at lower SVMC's, such as the 100-75-75 treatment, because the substrate at higher SVMC is closer to container capacity. For the control treatment higher irrigation volumes and higher SVMC would be expected to increase runoff and nutrient loss compared to irrigation based on DWU. In a related experiment with the same irrigation treatments runoff volumes from the control were greater on every measurement day and nitrate and phosphate losses were reduced on some measurement days compared to runoff volumes applied at 100% DWU and 75% DWU (Chapter 2).

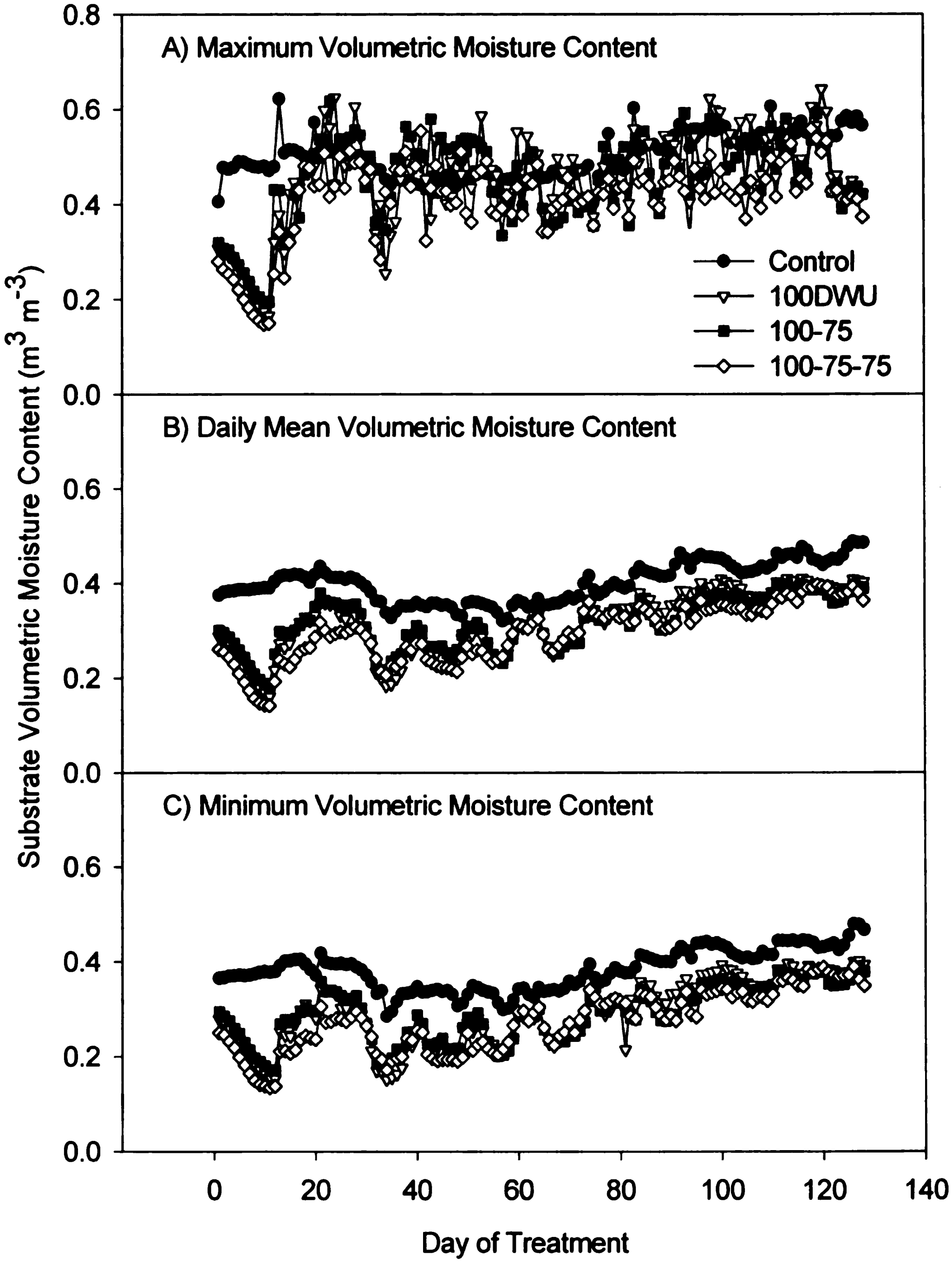

Figure 3.7. Daily maximum (A), mean (B), and minimum (C) substrate volumetric moisture content of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' irrigated with four irrigation treatments from day 1 (8 June 2007) to day 128 (13 October 2007). Daily moisture contents calculated from 3 containers per treatment except for the control and 100-75-75 treatments in which one container was excluded due to substantially different moisture contents than the other two containers.

Table 3.2. Overall daily maximum, mean, and minimum substrate volumetric moisture content of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' under four irrigation treatments from 8 June to 13 October 2007. Volumetric moisture content was measured in the top 6 cm of substrate. Measurements were made every minute, and 15 minute means recorded and used to calculate daily means.

	Daily Volumetric Moisture Content ($m^3 \cdot m^{-3}$)		
Treatment	Maximum	Mean	Minimum
Control[z]	0.501 a[y]	0.402 a	0.383 a
100DWU	0.458 b	0.318 b	0.293 b
100-75	0.453 b	0.317 b	0.291 b
100-75-75	0.411 c	0.296 c	0.275 c

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Means with the same letter in each column are not significantly different (α = 0.05). Means separation by Tukey's Test (α = 0.05). N = 1280 for mc measurements and one of the three containers in the Control and 100-75-75 treatments was excluded from analysis because data was substantially different from the other two containers in the same treatment.

Table 3.3. Total irrigation and water applied (irrigation + precipitation) to each 10.2 L container-grown *Spiraea fritschiana* 'Wilma' during 128 days from 8 June 2007 to 13 October 2007 under four irrigation treatments. Total precipitation was 281 mm and added 16 L to each container.

Treatment	Average Irrigation Applied Daily ($L \cdot container^{-1}$)	Total Irrigation Applied ($L \cdot container^{-1}$)	Total Water Applied ($L \cdot container^{-1}$)
Control[z]	1.07a[y]	137.0	153.0
100DWU	0.77b	98.4	114.4
100-75	0.67c	86.2	102.2
100-75-75	0.64c	82.0	98.0

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]Means with the same letter are not significantly different. Means separation by Tukey's Test ($\alpha = 0.05$; n = 128).

Diurnal Substrate Volumetric Moisture Content

Fifteen minute means of one minute measurements of SVMC for the three containers in each treatment are shown from 0600 HR of day 46 to 2345 HR on day 47 (Figure 3.8A – D). Morning irrigation events appear as peaks in SVMC. The varying time in peak SVMC resulted from irrigation zones running sequentially. Substrate volumetric moisture content declined steadily during the afternoon hours until approximately 1800 HR after which water loss from container substrate was minimal. Daily water use of *S. fritschiana* 'Wilma' on day 34 (the date of DWU measurement used to schedule irrigation applications in the concurrent study and the amount applied on days 46 and 47) was 1.06 L·container^{-1}. On day 46 the 100-75 and 100-75-75 treatments received 75% and 100% DWU. Overhead irrigation applications of 100% DWU and 75% DWU were 0.30 L·container^{-1} and 0.23 L·container^{-1} and additional volumes applied by hand were 0.76 L·container^{-1} and 0.57 L·container^{-1}. In Figure 3.8D, the overhead irrigation application occurred long enough after hand-watering that two peaks in SVMC are visible. The first peak is from the hand watering application of 0.76 L·container^{-1} and the second from the overhead application of 0.30 L·container^{-1}.

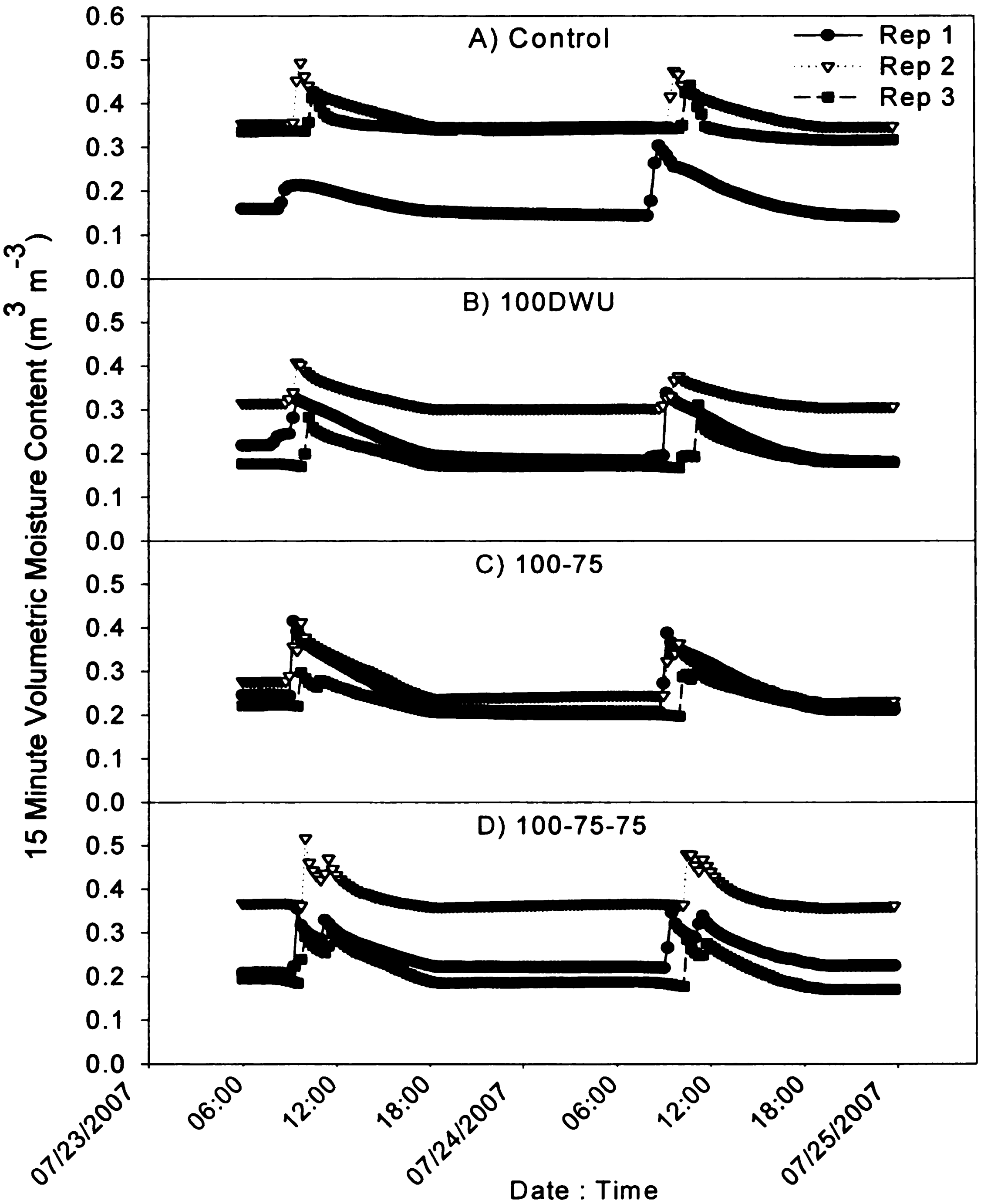

Figure 3.8. Substrate volumetric moisture content of three containers of four irrigation treatments from 0600 HR on 23 July 2007 (day 46) to 1345 HR on 24 July 2007 (day 47). Each data point is the 15 minute mean of 1 minute moisture content measurements.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100%DWU the first application followed by two applications of 75% DWU.

Substrate Temperature

Average daily substrate temperature of all treatments during the experiment was 22.5°C and closely followed the pattern of average daily air temperature (Figure 3.1B; Figure 3.9). Daily maximum substrate temperature of individual containers in all treatments was frequently above 30°C and exceeded 40°C (Figure 3.9A). The highest recorded daily maximum temperature of the 3 containers averaged together in each of the control, 100DWU, 100-75, and 100-75-75 treatments was 39.6°C (day 54), 41.3°C (day 10), 44.1°C (day 10), and 40.1°C (day 7), respectively (Figure 3.9A). The highest recorded substrate temperature for an individual container during the experiment was 47.6°C on day 32 at 1325 HR for rep 3 of the 100-75 treatment. Maximum air temperature at 1.5 m above the production area also exceeded 30°C but did not reach 40°C (Figure 3.1). Because irrigation times for each treatment replicate varied and the heights of different species surrounding each *S. fritschiana* 'Wilma' plant varied, thereby affecting incident solar radiation, the exact effect of irrigation volume on daily substrate temperatures could not be determined.

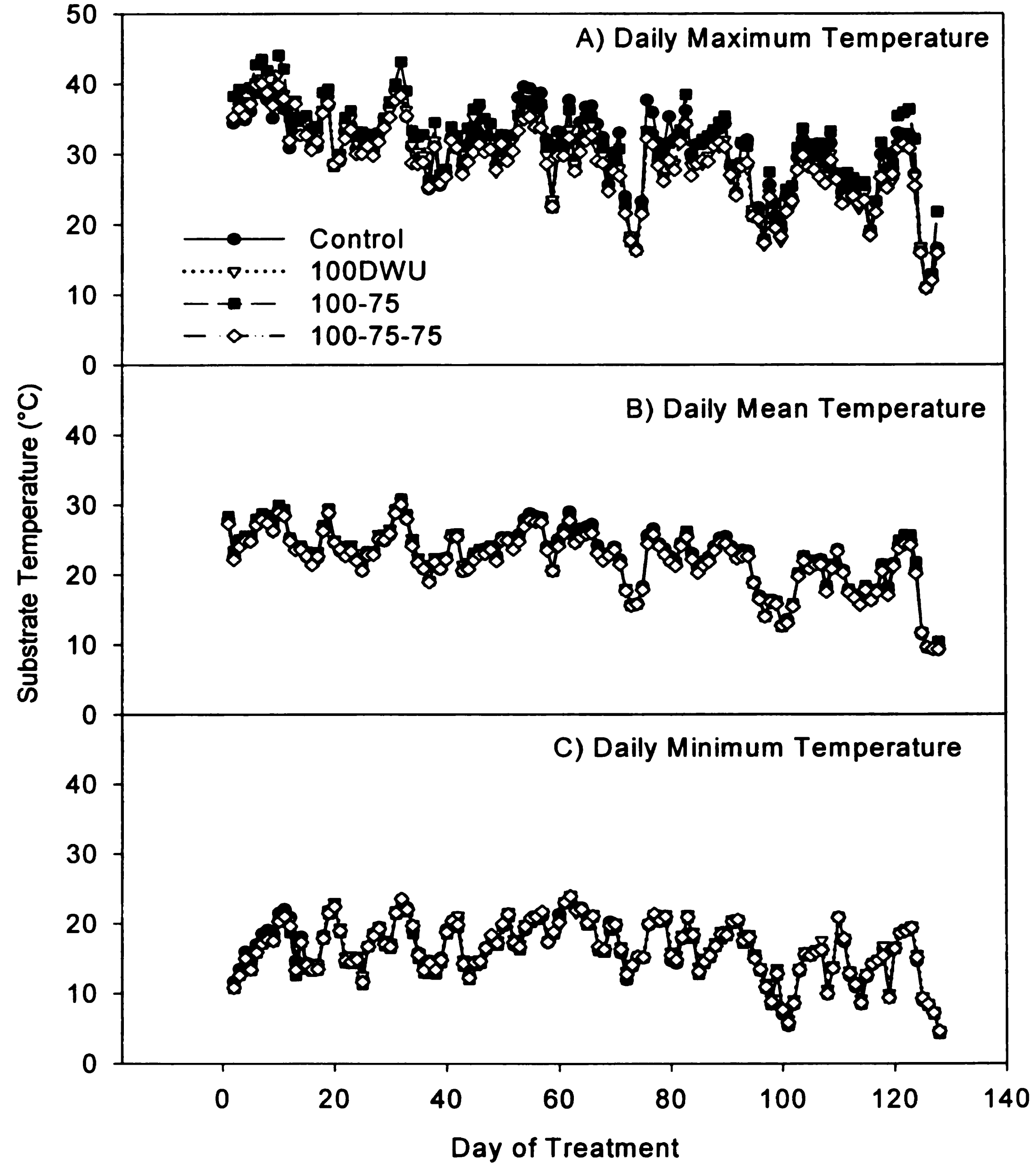

Figure 3.9. Daily maximum (A), mean (B), and minimum (C) substrate temperature of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' under four irrigation treatments. Each data point is the mean of substrate temperatures from three containers per treatment measured at a depth of 10 cm. Data is shown from day 2 of the experiment (9 June 2007) through day 128 (13 October 2007).

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100%DWU the first application followed by two applications of 75% DWU.

Fifteen minute means of 1 minute substrate temperatures are shown for days 10, 11, 46, and 47 in figure 3.10. On day 10 substrate temperatures of the control, 100DWU, 100-75, and 100-75-75 treatments were above 30°C for 10 h, 9.75 h, 10.5 h, and 10.25 h, respectively (Figure 3.10A). The 100-75 and 100-75-75 treatments were first to reach 30°C at 11:15 HR. The 100DWU and control treatments reached 30°C at 12:00 and 12:45 HR. Additionally, the 100DWU and 100-75 treatments were ≥ 40°C for 2 h and 4.25 h (Figure 3.10A). On day 11 the patterns were almost identical. On days 46 and 47 substrate temperatures of all treatments exceeded 30°C but did not reach 40°C (Figure 3.10B).

A possible concern when irrigating according to DWU is that reduced irrigation inputs may result in higher substrate temperatures that could damage or kill roots resulting in reduced top growth or prolonged transplant shock. Keever and Cobb (1984b) reported that the temperature of pine bark medium increased slower at higher moisture contents. In Georgia, Fretz (1971) reported substrate temperatures in # 1 containers without plants exposed to direct solar radiation exceeded 48°C. In Alabama Keever and Cobb (1984a) showed that summer substrate temperature of *Rhodendron* x ('Hershey's Red' Azalea) measured 2.5 cm in from the south wall of a 2.8 L black container at a depth of 10 cm increased during the morning and was above 40°C for most of the day.

Wong et al. (1971) reported reduced root growth of *Fouquieria splendens*, *Parkinsonia aculeate*, *Prunus persica*, *Robinia pseudoacacia*, and *Rosa* sp. after 4 h exposure to 40°C, and root tip death after 4 h exposure to temperatures between 40 and 45°C. In the present study there were 16 days on which the substrate temperature of at least one container exceeded 40°C with an average of 2.6 h per day above 40°C. The only containers that did not experience substrate temperatures in excess of 40°C during the experiment were rep 2 of the control and rep 3 of the 100-75-75 treatment. This was likely because of the sequential irrigation scheduling and shading caused by taller species in the concurrent study. The majority of days with substrate temperature in excess of 40°C occurred during the early part of the experiment. This was likely due to increased substrate exposure to direct solar radiation resulting from small plant canopies. For an individual container the greatest number of consecutive days with substrate temperature exceeded 40°C was 3 d. This occurred on days 6 – 8 for the 3 reps of the 100-75 treatment and rep 1 of the 100-75-75 treatment; days 31 – 33 for rep 3 of the 100-75 treatment; and days 53 – 55 for rep 1 of the control treatment and rep 3 of the control treatment. During these days substrate temperatures exceeded 40°C for ≥ 4 h for rep 2 of the 100-75 treatment on days 6 (5.25 h), 7 (4.25 h), and 8 (4.25 h) and for rep 3 of the control on days 54 (4.25 h) and 55 (4.25 h). For those containers that did experience temperatures in excess of 40°C the duration was seldom greater than 4 h. Plants exposed to these conditions early in the growing season would have time for root re-growth before the end of the season. Data from the concurrent irrigation study showed no differences in final GI among treatments for 18 plants per treatment (Chapter 1). Furthermore, Wong et al. (1971) reported that substrate temperatures in excess of 50°C killed roots and resulted in the death of tops of five woody plant species, but substrate temperatures in the current study did not exceed 50°C.

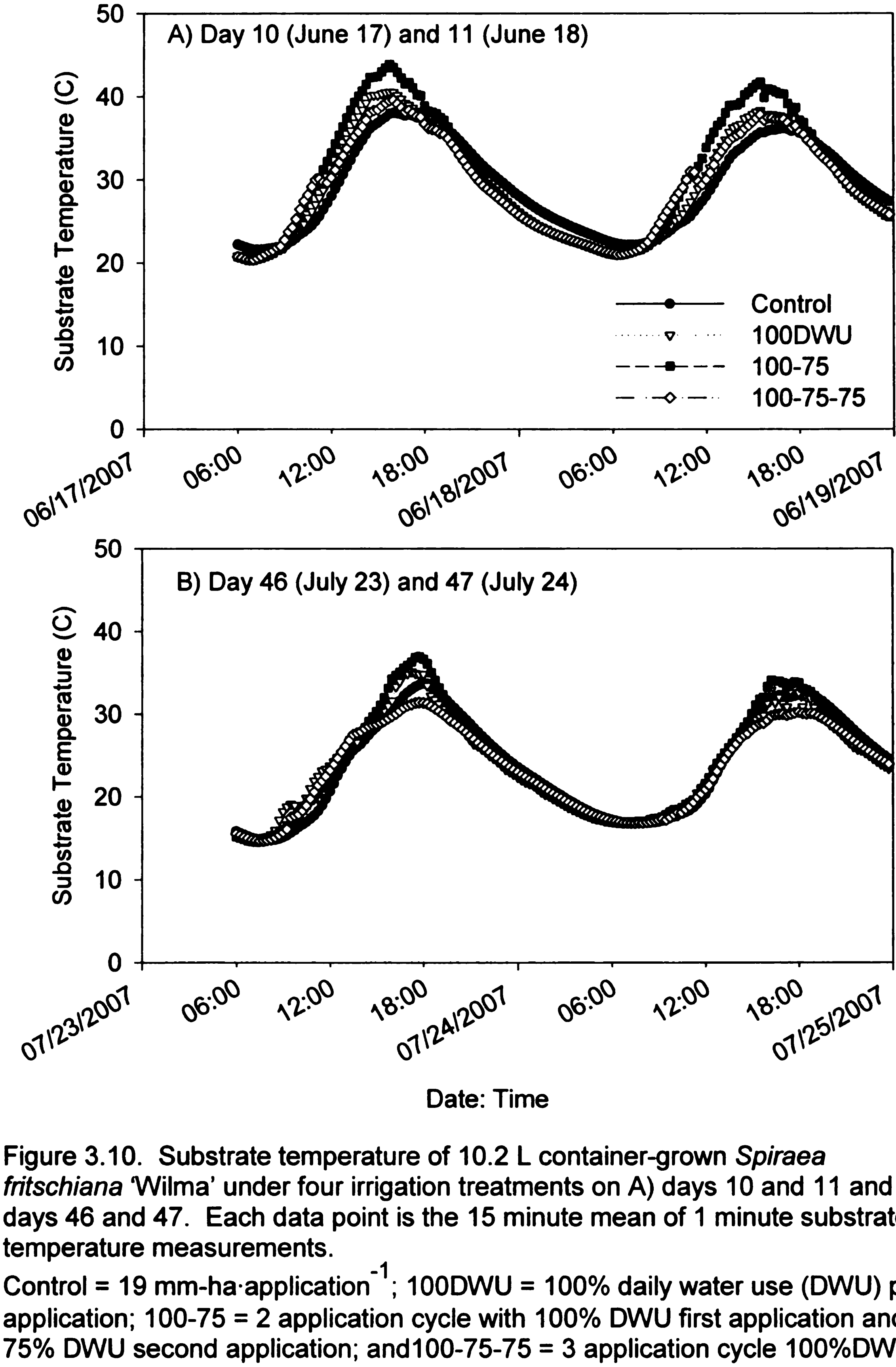

Figure 3.10. Substrate temperature of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' under four irrigation treatments on A) days 10 and 11 and B) days 46 and 47. Each data point is the 15 minute mean of 1 minute substrate temperature measurements.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100%DWU the first application followed by two applications of 75% DWU.

Relationship of ET_P and Growth Index to ET_A

Regression analysis was conducted on the four irrigation treatments. The dependent variable ET_A was log transformed to correct a potential problem of unequal variances that was indicated by a slight widening of the residuals from the residuals versus predicted values plot that was used to examine heteroscedasticity. Regression equations for each treatment are presented in Figure 3.11A – D. The relationship of $\log ET_A$ to ET_P in the control treatment was significant ($p = 0.0005$) with $R^2 = 0.43$. When GI was added to the model the R^2 increased from 0.43 to 0.62. Adding a quadratic term for GI to the model increased the R^2 to 0.70. The final model was significant ($p < 0.0001$) and the independent variables ET_P, GI, and GI^2 were significant with p = 0.0004, 0.0157, and 0.0284, respectively, n = 24 (Figure 3.11A).

The relationship of $\log ET_A$ to ET_P in the 100DWU treatment was significant ($p = 0.0013$) with $R^2 = 0.27$. The addition of GI improved the model substantially with $R^2 = 0.48$. Adding a quadratic term for GI did not improve the model. The final model was significant ($p < 0.001$) and the independent variables ET_P and GI were significant with $p < 0.0001$ and $p = 0.0008$, n = 36 (Figure 3.11B).

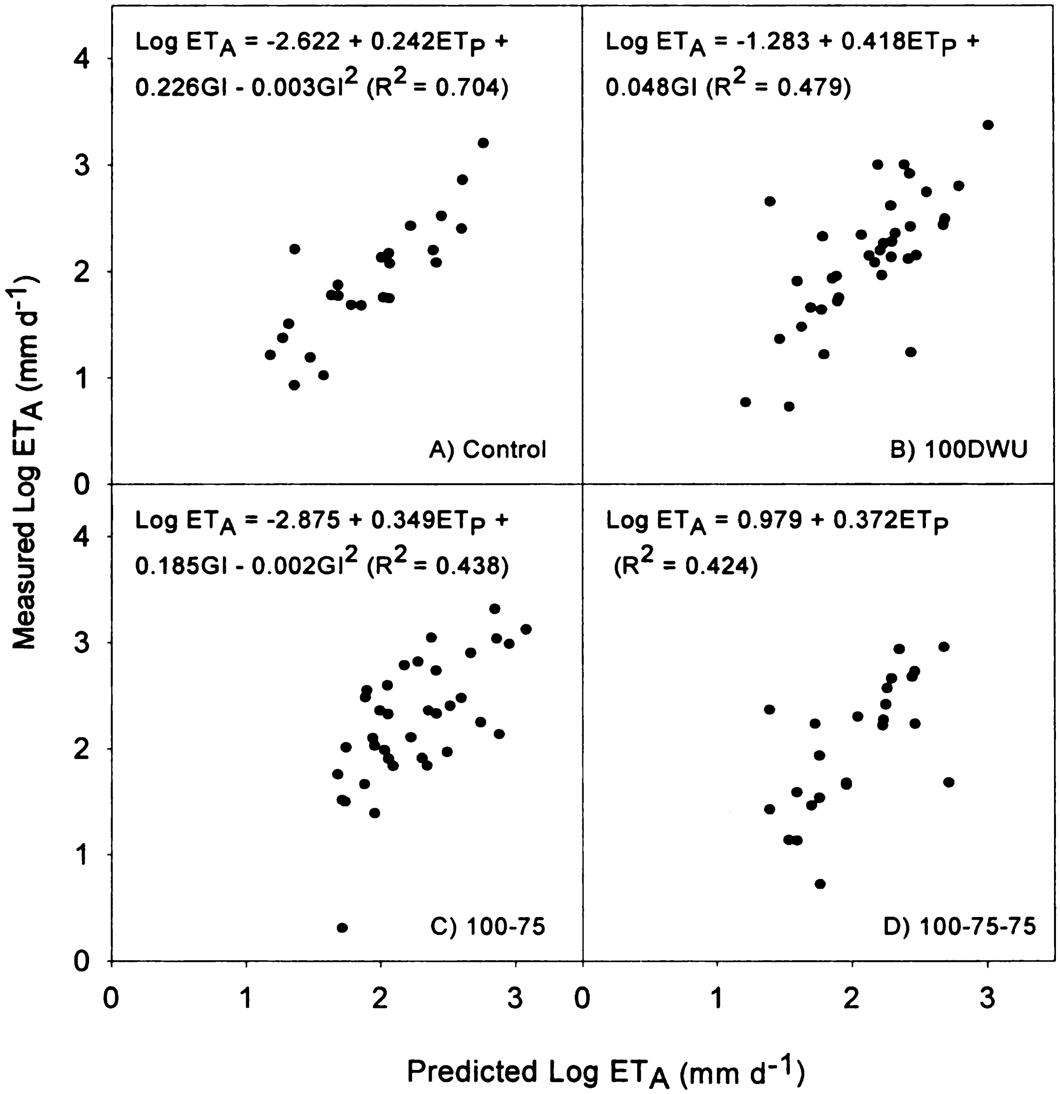

Figure 3.11. Daily ET_A vs. predicted ET_A from regression equations of the log transformed dependent variable ET_A as a function of daily reference potential evapotranspiration (ET_P) and growth index (GI) when significant for 10.2L container-grown *Spiraea fritschiana* 'Wilma' under four irrigation treatments (A - D) on 12 days during a 114 period from day 13 to day 127 after experiment initiation (day 1 = 8 June 2007). Each data point corresponds to daily ET_A measured from one plant. For A and D there were two plants measured each day, and for B and C there were three plants measured each day.

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and100-75-75 = 3 application cycle 100%DWU the first application followed by two applications of 75% DWU.

The relationship between $\log ET_A$ and ET_P in the 100-75 treatment was significant ($p = 0.0002$), with $R^2 = 0.35$. The addition of the linear and quadratic variables for GI resulted in $R^2 = 0.44$ and the model was significant ($p < 0.0003$). The final model included the independent variables ET_P, GI, and GI^2 which were significant with $p < 0.0001$, $p = 0.0283$, and $p = 0.0289$ respectively, $n = 36$ (Figure 3.11C).

The relationship of $\log ET_A$ to ET_P in the 100-75-75 treatment was significant ($p = 0.0006$), with $R^2 = 0.42$, $n = 24$ (Figure 3.11D). Growth index was not significant when added to the model ($p = 0.91$) and R^2 did not increase, even though the model was significant ($p = 0.0030$).

Correlation of ET_P to ET_A may have been improved if GI had been measured more frequently during the experiment or if irrigation was applied to all containers in each treatment at the same time. Additionally, hand watering of the three DWU treatments sometimes resulted in two peaks in substrate volumetric moisture content (Figure 3.8D). When two peaks were present our estimates of ET_A were based on water loss one hour after the second peak, and did not include water loss in the time between the overhead irrigation and hand watering. On these days, ET_A was underestimated by an amount dependant on the time between overhead and hand watering. This factor likely contributed to the lower correlation of ET_P to ET_A for the three DWU treatments compared to the control in which daily irrigation was applied in one application by the overhead system.

Beeson (1993) reported correlation of ET_P to ET_A during the last six months of production for 10.2 L container-grown *Rhododendron* sp. 'Formosa' during three periods: quiescent (days 0 to 59), rapid shoot growth (days 72 to 94), and canopy recovery from a hard freeze (days 140 to 172) with r = 0.7790, 0.4910, and 0.67, respectively. Daily ET_A was calculated for each plant by summing hourly weight loss of each container. During the 22 day period of rapid shoot growth Beeson (1993) obtained a correlation of r = 0.4910 (R^2 = 0.2411), and attributed the weak correlation to a higher ET_A to ET_P ratio during the middle of the period than at the beginning and the end. When daily ET_A and ET_P were summed over a four day period the correlation of the model improved to r = 0.8754 (R^2 = 0.7763) which is similar to the relationship obtained by the model for the control treatment in this study (R^2 = 0.704). Beeson's (1993) models during each period and when daily ET_A and ET_P were summed over a four day period were not significantly improved by the addition of canopy characteristics. Beeson (1993) attributed the absence of canopy effect to pruning and a hard freeze. Knox (1989) reported linear regression equations to predict water use that included ET_P estimated by the Thornthwaite method and growth index for five container-grown woody landscape plants with R^2 values ranging from 0.26 to

0.81. Linear equations using the variables of pan evaporation and growth index were more highly correlated to water use with R^2 values ranging from 0.78 to 0.88 (Knox, 1989). The significant relationships of ET_A to ET_P and canopy characteristics reported by Knox (1989) and the current study show the potential of these relationships to be developed into functional models to schedule irrigation with further research and validation.

Crop Coefficients

Crop coefficients (K_C) were calculated as: $K_C = ET_A / ET_P$. Crop coefficients were calculated for the 12 days that ET_A was calculated for regression analysis. ET_A, ET_P, and calculated K_C are shown in Figure 3.12A – C. During the experiment K_C values in all treatments fluctuated considerably (Figure 3.12C). The lowest and highest crop coefficient values of the control, 100DWU, 100-75, and 100-75-75 treatments were 1.7 (day 79) and 3.5 (day 117), 1.7 (day 13) and 4.3 (day 60), 2.0 (day 13) and 5.4 (day 34), and 1.6 (day 117) and 6.7 (127), respectively (Figure 3.12C). Because irrigation application time varied and irrigation applications varied in length on each DWU measurement day K_C values among treatments and days were not compared. However, the study provided the first information on water use and K_C values of container-grown *S. fritschiana* 'Wilma'. Fluctuations in K_C values during the experiment were similar to seasonal fluctuations of high water requiring species reported by Schuch and Burger (1997) that ranged from 1 to 4.7. Niu et al. (2006) also reported that water use and K_C fluctuated with date of measurement, and that four month averages of K_C values for five species of container-grown woody landscape plants ranged from 0.93 to 1.74. Crop coefficients similar to those measured in the current study which ranged from 1.7 to 6.7 have been measured for other species of container-grown woody ornamentals with values ranging from <1 to > 5 (Burger et al., 1987; Regan, 1994). The wide range of reported K_C values of container-grown plants reported is due to a number of factors including: method used to calculate ET_A and ET_P, time (early or late) in the growing season, (Irmak, 2005), seasonal fluctuations, plant growth, location (Schuch and Burger (1997), container spacing (Burger et al., 1987), and species (Niu et al., 2006).

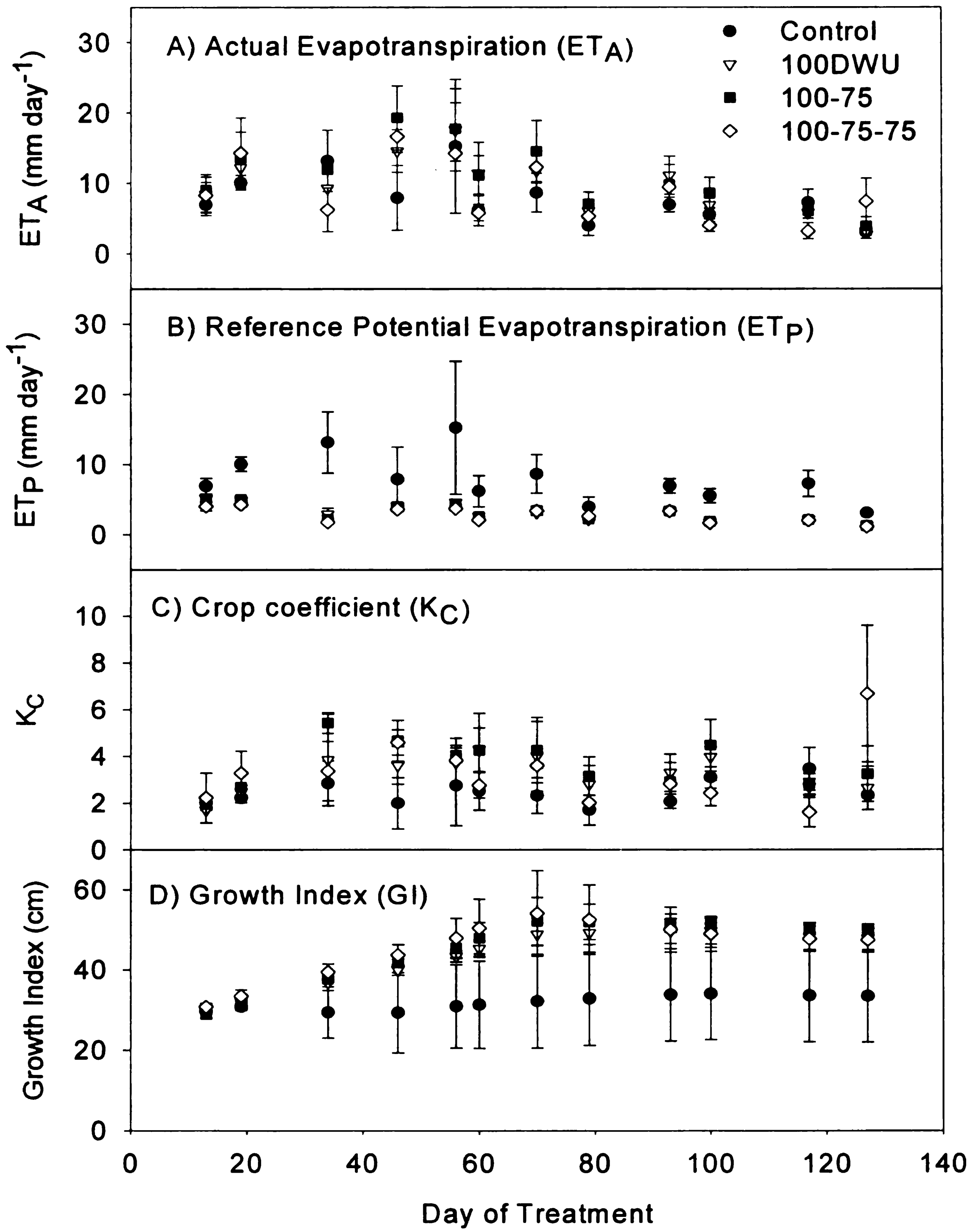

Figure 3.12. Actual evapotranspiration (A), potential evapotranspiration (B), crop coefficient (C), and growth index (D) of container-grown *Spiraea fritschiana* 'Wilma' grown under four irrigation treatments. Error bars represent standard error of treatment means. Day 1 = 8 June 2007. n = 2 for the control and 100-75-75 treatments and 3 for the 100DWU and 100-75 treatments.

Estimated GI on each measurement date followed a similar pattern to K_C values, but there was a lag between peak GI and peak K_C and ET_A of the three DWU treatments (Figure 3.12D). The large variation and low GI values for the control treatment was due to limited replication of only 2 plants, one of which was damaged between days 19 and 34. Although the GI of the control treatment appears lower than the 3 DWU treatments in Figure 3.12D, there was no difference among treatments in final GI of *S. fritschiana* 'Wilma' in the concurrent study where the GI of each treatment was the mean of 18 plants (Chapter 1). Final GI means ± standard error of the mean in the concurrent study for the control, 100DWU, 100-75, and 100-75-75 treatments were 48 ± 2, 49 ± 1, 48 ± 1, and 51 cm ± 1 cm, respectively (Chapter 1). Strong relationships between GI and K_C have been reported by Irmak (2005) who developed third order polynomial equations for summer and fall using GI as a function of days after transplanting to estimate weekly K_C values for *Viburnum odoratissimum* (Ker.-gawl) grown in a white Multi-Pot Box System with R^2 = 0.99 for both summer and fall. Research by Beeson (2004) on *Ligustrum japonicum* L. showed that calculations of K_C based on ET_A normalized by projected canopy area as a function of percent canopy closure were strongly correlated R^2 = 0.951 and has potential for developing models to predict K_C for container-grown woody plants. The model was tested for functionality and performed well conserving water and meeting the objective of 90% marketable sized plants 3 weeks faster than a manually controlled irrigation schedule (Beeson and Brooks, 2008).

Conclusions

Substrate volumetric moisture content of container-grown *S. fritschiana* 'Wilma' was affected by irrigation treatment with higher SVMC in treatments receiving greater irrigation volumes. The exact effect of irrigation volume on substrate temperature among treatments could not be determined due to variable irrigation times and plant shading within each treatment replicate. However, substrate temperatures exceeded 40°C mostly early in the season and for durations rarely over 4 hours. Effects of substrate temperature on plant growth among treatments were unlikely because there were no differences in final GI among treatments in a concurrent irrigation study using the same plants plus others during the same time period.

Significant relationships of ET_A to ET_P and GI in this study show potential for further model development for irrigation scheduling, despite limitations placed on the current study from variable irrigation timing and hand watering associated with a concurrent study. In addition stronger correlations would be expected with more plant replicates and more GI measurement dates. This study also reported K_C values of *S. fritschiana* 'Wilma' from mid-June through mid-October. Because K_C coefficient values varied during the season, seasonal values would be required in irrigation scheduling. Based on recent work by Beeson (2004) and

Beeson and Brooks (2008) future research investigating the relationship between K_C and percent canopy closure is needed. Percent canopy closure is easily estimated and could be implemented into a study continuing the investigation of the relationship of ET_A to ET_P and GI for *S. fritschiana* 'Wilma' developed in this study or for any other container-grown woody ornamental of interest. Models selected for further testing and validation would be based on variables providing the strongest relationships.

Literature Cited

Anonymous. 1999. ThetaProbe soil moisture sensor. User Manual ML2-UM-1.21. Delta-T Devices Ltd. Cambridge, England.

Anonymous. 2008. Michigan State Climatologist's Office. Webpage: http://climate.geo.msu.edu/stations/2395/
Accessed: 11/17/2008.

Beeson, Jr., R.C. 1993. Relationship of potential evapotranspiration and actual evapotranspiration of *Rhododendrom* sp. 'Formosa'. Proc. Fla. State. Hort. Soc. 106:274 – 276.

Beeson, Jr., R.C. 2004. Modelling actual evapotranspiration of *Ligustrum japonicum* from rooted cuttings to commercially marketable plants in 12 liter black polyethylene containers. IVth IS on Irrigation of Hort. Crops. Acta Hort. 664, ISHS 2004.

Beeson, Jr., R.C. 2005. Modeling irrigation requirements for landscape ornamentals. HortTechnology. 15(1):18 – 22.

Beeson, Jr., R.C. and J. Brooks. 2008. Evaluation of a model based on reference crop evapotranspiration (ET_0) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Proc. Vth IS on Irrigation of Hort. Crops. Acta Hort. 792, ISHS 2008.

Blonquist, Jr., J.M., S.B. Jones, and D.A. Robinson. 2005. Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems. Vadose Zone Journal. 4:1059 – 1069.

Burger, D.W., J.S. Hartin, D.R. Hodel, T.A. Lukaszewski, S.A. Tjosvold, and S.A. Wagner. 1987. Water use in California's ornamental nurseries. Calif. Agric. Sep – Oct: 7 – 8.

Cornejo, C., D.Z. Haman, and T.H. Yeager. 2005. Evaluation of soil moisture sensors, and their use to control irrigation systems for containers in the nursery industry. ASAE Meeting Paper No. 054056. St. Joseph, MI: ASAE.

Doorenbos, J. and W.O. Pruit. 1975. Guidelines for predicting crop water requirements. FAO Irrigation Drainage Paper 24.

Eller, H., and A. Denoth. 1996. A capacitive soil moisture sensor. J. Hydrology. 185(1/4):137 – 146.

Fretz, T.A. 1971. Influence of physical conditions on summer temperatures in nursery containers. HortScience. 6(4): 400 – 401.

Garcia y Garcia, A., G. Hoogenboom, and L. Guerra. 2004. Container temperature and moisture for estimating evapotranspiration of nursery crops. ASAE/CSAE Meeting Paper No. 042295. St. Joseph, Mich. ASAE.

Hanson, B.R. and D. Peters. 2000. Soil type affects accuracy of dielectric moisture sensors. California Agriculture. 54(3):43 – 47.

Irmak, S. 2005. Crop evapotranspiration and crop coefficients of *Viburnum odoratissimum* (Ker.-Gawl). Applied Engineering in Agriculture. 21(3):371 – 381.

Keever, G.J. and G.S. Cobb. 1984a. Container and production bed mulch effects on media temperatures and growth of 'Hershey's Red' Azalea. HortScience. 19(3):439 – 441.

Keever, G.J. and G.S. Cobb. 1984b. Growth medium temperature in containers as influenced by moisture content. J. Environ. Hort. 2(1):21 – 22.

Kincaid, D.C., and D.F. Heerman. 1974. Scheduling irrigations using a programmable calculator. USDA-ARS-NC-12. Washington, D.C.: U. S. Gov. Print Office.

Knox, G.W. 1989. Water use and average growth index of five species of container grown woody landscape plants. J. Environ. Hort. 7(4):136 – 139.

Niu, G., D.S. Rodriguez, R. Cabrera, C. McKenney, and W. Mackay. 2006. Determining water use and crop coefficients of five woody landscape plants. J. Environ. Hort. 24(3):160 – 165.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Royal Soc. London A. 193:120 – 146.

Regan, R.P. 1994. Variation in water use of container-grown plants. Comb. Proc. Intl. Plant Prop. Soc. 44:310 – 312.

Schuch, U.K., and D.W. Burger. 1997. Water use and crop coefficients of woody ornamentals in containers. J. Amer. Soc. Hort. Sci. 122(5):727 – 734.

Thornthwaite, C.W. 1944. Report of the committee on transpiration and evaporation. 1943 – 44. Trans. Amer. Geophys. Union 25:683 – 693.

Topp, G.C., and J.L. Davies. 1985. Time-domain-reflectometry (TDR) and its application to irrigation scheduling. In Advances in Irrigation, ed., D. Hillel, 107 – 127. San Diego, Calif.: Academic Press.

Tyler, H.H., S.L. Warren, and T.E. Bilderback. 1996. Cyclic irrigation increases irrigation application efficiency and decreases ammonium losses. J. Environ. Hort. 14:194 – 198.

Warren, S.L. and T.E. Bilderback. 2005. More plant per gallon: Getting more out of your water. HortTechnology. 15(1):14 – 18.

Wong, T.L., R.W. Harris, and R.E. Fisell. 1971. Influence of high soil temperatures on five woody-plant species. J. Ameri. Soc. Hort. Sci. 96(1):80 – 82).

Yeager, T.H. 2003. Implementation guide for container-grown plant interim Measure. EDIS Document ENH-895. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. Webpage: http://edis.ifas.ufl.edu/EP152 Accessed 01/23/2008.

Yeager, T., C. Gilliam, T. Bilderback, D. Fare, K. Tilt, and A. Niemiera. 1997. Best management practices guide for producing container-grown plants. Southern Nursery Association, 1000 Johnson Ferry Road, Suite E-130, Marietta, GA 30068 – 2100.

Yoder, R.E., D.L. Johnson, J.B. Wilkerson, and D.C. Yoder. 1998. Soil water sensor performance. Applied engineering in Agriculture 14(2):121 – 133.

CHAPTER FOUR

CONCLUSIONS AND FUTURE DIRECTION OF CONTAINER NURSERY IRRIGATION MANAGEMENT TO REDUCE WATER USE, RUNOFF, AND OFF-SITE MOVEMENT OF AGRICULTURAL CHEMICALS

CONCLUSIONS AND FUTURE DIRECTION OF CONTAINER NURSERY IRRIGATION MANAGEMENT TO REDUCE WATER USE, RUNOFF, AND OFF-SITE MOVEMENT OF AGRICULTURAL CHEMICALS

Research Summary

During mid June through mid October of 2006 and 2007 twenty species of container-grown woody ornamentals were subjected to irrigation schedules based on a percentage of plant daily water use or a traditional irrigation rate to evaluate effects on plant growth and water conservation. Four irrigation treatments were imposed: 1. a control irrigation rate of 19 mm-ha$\cdot^{-1}$; 2. irrigation scheduled to replace 100% daily water use (DWU) during each application (100DWU); 3. irrigation alternating every other application with 100% replacement of DWU and 75% DWU (100-75); and 4. irrigation scheduled on a three application cycle replacing 100% DWU the first application followed by two applications replacing 75% DWU (100-75-75). During the 2006 experiment, treatments were applied daily from 14 June to 30 September and every other day from 1 Oct. to 13 Oct. 2006. During 2007, treatments were applied daily from 8 June to 13 Oct. 2007. Four of the species from the 2006 irrigation experiment were grown for a second season under the same irrigation treatments in a runoff and nutrient loss experiment from 8 June to 30 Sept. 2007.

During the 2006 and 2007 irrigation experiments and the runoff experiment irrigation scheduling according to the three DWU treatments conserved water for every species over the experiment duration. Total irrigation inputs by the DWU treatments were 25% to 75% lower than the control depending on species and DWU treatment. At some point during the experiments DWU of six species exceeded the daily irrigation amount of the control. This data emphasizes the importance of irrigation scheduling based on actual instead of perceived water use and that under a fixed irrigation schedule plants can not only be over-watered but under-watered. In addition 19 of the 20 species were classified as heavy, moderate, or low water users based on average DWU and total water applied during the experiments so that growers can group species with similar water uses together to minimize over-watering. *Syringa* × *prestoniae* McKelv. 'Donald Wyman' was removed from analysis due to poor plant growth. It should be noted that these classifications were based on data from one growing season in central Michigan and water use for these species will vary depending on location and climate.

Final plant size for all species under DWU treatments was greater or equal to the control, indicating that irrigation can be substantially reduced without negatively impacting plant growth. Increased growth by plants in DWU treatments compared to the control was likely due to higher nutrient content available for uptake in the substrate because of less leaching than the control. Data from the runoff experiment provides evidence of this because on 4 of 8 runoff collection days quantities of NO_3^--N recovered from control production areas were higher than NO_3^--N quantities recovered from production areas that received irrigation volumes corresponding to 100% or 75% DWU.

The runoff study also showed that irrigation scheduling based on DWU was successful in reducing runoff volume compared to the control on all eight measurement days. Average runoff from all 8 days was 46% and 60% less for the 100% DWU and 75% DWU irrigation volumes compared to the control. In addition percent irrigation recovered as runoff for the 100% DWU and 75% DWU was lower on 5 of the 8 days compared to the control. Across all days for the control, 100% DWU, and 75% DWU irrigation volumes 60%, 37%, and 32% of applied irrigation was captured as runoff.

Leachate electrical conductivity (EC) was measured during the irrigation and runoff experiments during 2007 to investigate effects of irrigation volume on soluble salt accumulation in the container substrate. Electrical conductivity levels were high in June, probably due to low nutrient uptake by small plants at this time and possible accumulation during the winter months when irrigation was not applied. However, on all subsequent measurement dates EC levels of all treatments were within or slightly above levels recommended for container-grown plants fertilized with controlled-release fertilizers. Precipitation was not excluded and therefore likely influenced soluble salt levels in containers, but what to what effect was not determined. Together these three experiments showed that irrigating according to DWU conserved water and reduced runoff and nutrient loss from containers, without an unacceptable accumulation in soluble salts compared to a traditional irrigation rate.

During the 2007 irrigation study relationships of actual evapotranspiration (ET_A) to potential evapotranspiration (ET_P) and growth index (GI) were found for all treatments for *Spiraea fritschiana* 'Wilma'. Significant relationships were found in all treatments, with R^2 values for the control, 100DWU, 100-75, and

100-75-75 treatments of 0.704, 0.479, 0.438, and 0.424, respectively. Models for the control and 100-75 treatments included the independent variables ET_P, GI, and GI^2. The model for the 100DWU treatment included the variables ET_P and GI. The only variable in the model for the 100-75-75 treatment was ET_P.

Crop coefficients (K_C) of *S. fritschiana* 'Wilma' were estimated for the 12 days that DWU was measured for irrigation scheduling in the concurrent irrigation study. The highest and lowest crop coefficient values of the control, 100DWU, 100-75, and 100-75-75 treatments were 1.7 (day 79) and 3.5 (day 117), 1.7 (day 13) and 4.3 (day 60), 2.0 (day 13) and 5.4 (day 34), and 1.6 (day 117) and 6.7 (127), respectively. These were the first K_C values reported for *S. fritschiana* 'Wilma'. Reported K_C values were in a range similar to those reported for other container-grown woody ornamentals. Fluctuation in K_C values during the growing season was likely due to different stages of plant growth, canopy coverage, and weather conditions.

The significant relationships of ET_A to ET_P and GI reported could have possibly been improved by more frequent GI measurements, more plant replications, and more frequent measurement days. The lower R^2 values of the three DWU treatments compared to the control probably resulted from hand watering, which was required when the DWU of *S. fritschiana* 'Wilma' exceeded the DWU of the species with the lowest DWU in the concurrent study. Overhead irrigation was applied at the volume required to replace the 100% or 75% DWU of the species in the concurrent study with the lowest DWU so as not to over-water species with higher DWU's. Nonetheless, the significant relationships reported in this experiment show promise that with further research and validation, models capable of irrigation scheduling can be developed.

In future experiments on model development one irrigation event would be applied at the 100% DWU of a particular species or cultivar. The experimental design would consist of only the species or cultivar under investigation to minimize canopy effects and simulate an actual production setting. For example to further investigate the relationships reported in this experiment *S. fritschiana* 'Wilma' would be irrigated according to 100% DWU. Each replicate would be a plant with an installed soil moisture sensor. Using one irrigation treatment with the current number of ThetaProbes would increase our replications from 3 to 12 giving us a larger sample size. In addition to GI, canopy volume and percent canopy closure could be also calculated as described by Beeson (2004) and evaluated for model inclusion. The model developed by Beeson (2004) was evaluated by Beeson and Brooks (2008) and produced 90% marketable plants as a manually controlled irrigation treatment but did so three weeks faster and using 400 mm less irrigation. The evaluated model used the previous days reference evapotranspiration (ET_0) and a water needs index (WNI: a crop coefficient like variable based on percent canopy closure) to schedule and irrigate container-grown *Ligustrum japonicum*. One of the strengths of such a model is that it calculates the amount of irrigation to apply based on the previous days ET_0 and once set up with a datalogger only requires the grower to measure and input plant growth to calculate percent canopy closure. Real-time irrigation scheduling would be advantageous over irrigation applications scheduled from DWU measurements made periodically throughout the growing season because irrigation applications would be applied according to conditions that influenced ET_0 the day before application. Although the model would be species specific, once working models have been developed and validated for several species the process for modeling irrigation requirements of other species would follow.

Advancements in technology has allowed the use of multiple soil moisture sensors to measure ET_A or to estimate K_C values for irrigation scheduling with increasing accuracy and precision. When using soil moisture sensors it is important to make sure the sensing rods make good contact with the substrate. Another factor to consider when using moisture sensors is depth of sensor installation. Rod length for the ThetaProbe is 60 mm and in the experiments reported here volumetric substrate moisture content was measured within 60 mm from the surface. Water lost through evaporation would occur from the surface, leading to a gradient of increasing moisture content moving deeper in the substrate from the surface. Evidence of this was seen during a 33 day dry-down conducted on the substrate used in the experiment comparing volumetric moisture content measurements between a ThetaProbe and a balance. Average volumetric moisture content over the 33 day period from the ThetaProbe was on average 0.11 $m^3.m^{-3}$ lower than volumetric moisture content measured using the balance. For growers making hand-held on-the-spot measurements, measuring DWU deeper in the substrate may not be practical, but for in situ installations a deeper installation depth would likely provide volumetric moisture contents that are more representative of the entire substrate volume. Future research is needed to determine the effects of sensor placement on attaining the most representative volumetric moisture content measurement of the entire substrate volume.

Future Research

Future research on DWU based irrigation scheduling using soil moisture sensors should include data acquisition regarding the DWU for a variety of diverse species and cultivars over a number of growing seasons. Documenting seasonal effects on water use of a particular species will allow more accurate classification into a water use category. As the number of species evaluated increases it will be likely that the boundaries between water use classifications will become better defined as the particular species we evaluated may have resulted in the narrow differences in classification. Additionally, more than 3 classifications of water use may be required, i.e. moderate to low. There still exists some subjectivity when classifying plants by water use, but the data provided by future studies would provide growers with much needed scientific data regarding the water requirements of container-grown plants. Water use data will allow growers to group similar species together and irrigate according to the species within that group with the highest DWU. Doing so will reduce over-watering and under-watering associated with a fixed irrigation schedule and will reduce runoff and losses of agricultural chemicals to the environment.

These experiments will also provide data to estimate K_C values for container-grown plants. Like water use data, K_C data for container-grown woody ornamentals is limited. Estimated K_C values would be used in model development using canopy characteristics; such as GI, canopy volume, and percent canopy closure; and ET_0 with the goal of producing predictive models to calculate actual evapotranspiration (ET_A). The final step would be model validation whereby irrigation scheduled using model estimates of ET_A would be compared with irrigation scheduled from ET_A measurement using soil moisture sensors or weighing lysimeters. Such a comparison would allow the accuracy and performance of the model to be tested. Models should also be tested against a traditional irrigation rate to quantify water conservation. Model development for every species and cultivar is highly unlikely, but hopefully models will be adaptable to related species or to various other cultivars of the same species. Thus, a specific model could be used for a representative group of plant species and cultivars.

Water is one the most important resources for life on earth, and the importance of conserving clean supplies of water has never been more vital. Evidence of this fact is the regulations and restrictions that have been implemented and enforced not only in the agricultural sector, but in our personal lives as well. With more humans on the planet than have ever lived at one time before it is important that all industries not only those that use water for irrigation find ways to conserve water supplies and prevent contamination of those supplies. Our studies have shown that irrigation scheduling according to plant daily water use conserves water and reduces runoff compared to a traditional irrigation rate. By implementing similar practices in the production of container-grown woody ornamentals the container nursery industry can help ensure a clean supply of water for generations to come.

Literature Cited

Beeson, Jr., R.C. 2004. Modelling actual evapotranspiration of *Ligustrum japonicum* from rooted cuttings to commercially marketable plants in 12 liter black polyethylene containers. IVth IS on Irrigation of Hort. Crops. Acta Hort. 664, ISHS 2004.

Beeson, Jr., R.C. and J. Brooks. 2008. Evaluation of a model based on reference crop evapotranspiration (ET_0) for precision irrigation using overhead sprinklers during nursery production of *Ligustrum japonica*. Proc. Vth IS on Irrigation of Hort. Crops. Acta Hort. 792, ISHS 2008.

APPENDICES

APPENDIX A

THETAPROBE SUBSTRATE SPECIFIC CALIBRATION

THETAPROBE SUBSTRATE SPECIFIC CALIBRATION

Substrate Specific Calibration

The ThetaProbe is a type of dielectric soil moisture sensor and is lightweight, portable, and designed to provide instantaneous measurements of volumetric soil or substrate moisture content. Volumetric moisture content is the ratio between the volume of water in the substrate to the total volume of the sample and is expressed as a percentage (% volume) or as a ratio ($m^3 \cdot m^{-3}$) with 0% being completely dry and pure water being 100%. The sensing array is comprised of four stainless steel rods 60 mm in length, one in the center and three equally spaced on the outside forming a cylinder with a 30 mm diameter (Gaskin and Miller, 1996). The ThetaProbe measures soil moisture content within this cylinder of approximately 420 mm^3. Sensitivity to moisture content is biased towards the center rod and decreases moving outward in the cylindrical sampling volume. ThetaProbe measures volumetric soil water content by sending a 100MHz sinusoidal signal, chosen to minimize ionic conductivity effects, through the rods which are inserted into the material to be measured. The sensing array's impedance affects the reflection of the signal within the sampling volume and these reflections together with the applied signal form a standing wave along the transmission line. The impedance of the sensing array depends on the impedance of the soil and the impedance of the soil is related to its apparent dielectric constant (Anon., 1999). The relationship between the square root of the soil dielectric constant and volumetric moisture content has been documented by Topp et al. (1980), Whally (1993), and White et al. (1994).

The dielectric constant of water is approximately 81, and is much greater than most soil materials, usually between 3 and 4, and that of air which is around 1. As a result the dielectric constant of the soil depends mostly on the water content (Anon., 1999). The difference in amplitude of the generated standing wave is measured at two points giving the impedance of the sensing array, the dielectric constant of the soil, and thus the volumetric soil moisture content. The accuracy of the ThetaProbe has been well documented. Hanson and Peters (2000) obtained coefficients of determination between 0.64 and 0.91 for soil moisture readings taken from an uncalibrated ThetaProbe in 6 different soil types.

To improve the accuracy of the ThetaProbe measurements, a substrate specific calibration was conducted as outlined in pages 11 and 12 of the ThetaProbe Type ML2x user manual (Anon., 1999). In this calibration, direct voltage output from the ThetaProbe is fitted to a 3rd order polynomial equation ($R^2 = 0.998$) derived from the calibration procedure performed on the substrate.

$$\theta = \frac{\left[1.07 + 6.4V - 6.4V^2 + 4.7V^3\right] - 1.1893}{7.2201}$$

Where θ = volumetric moisture content and V = ThetaProbe direct output in Volts (Anon., 1999).

The substrate specific calibration reduces the output error associated from the ThetaProbe from ±0.05 to ±0.01 (Anon., 1999). Other sources of error include sampling errors resulting from soil heterogeneity, insertion errors, rocks (do not represent a source of error with this container substrate), air pockets, and roots in the sampling volume making contact with the rods (±0.04). The expected overall error term for the ThetaProbe output when using a substrate specific calibration can be expected to be ±0.05 (ThetaProbe output error ±0.01 + sampling error ±0.04).

When making hand-held measurements the ThetaProbe was inserted from the surface of the substrate with the rods perpendicular to the substrate surface. When measuring directly from the top surface of the substrate the potential exists for underestimating actual volumetric moisture content of the entire substrate volume. The measuring rods are 60 mm long, but the container has a depth of 240 mm, consequently if higher concentrations of water existed deeper in the container it would not be accounted for by the measurement taken from the top 60 mm of substrate. To address the magnitude of a possible under-measurement of volumetric soil moisture content a 33 day dry down was conducted. Substrate volumetric moisture content determined by a calibrated ThetaProbe was compared with water loss calculated from a balance. The dry down also provided a check of the accuracy of volumetric soil content measured by the ThetaProbe as compared to substrate moisture content determined from the balance.

Ten #3 (10.2 L) containers were filled with a nursery potting substrate comprised of 85% pine bark:15% peat moss (vol:vol) and irrigated to saturation and allowed to drain for one hour. This was the same substrate for which the ThetaProbe calibration equation was derived and the same substrate used in the field experiments. Containers were then weighed on a Mettler PM30 balance

(Mettler-Toledo, Inc., Columbus, OH). Volumetric moisture content of the substrate was measured at 3 different locations from the surface of the substrate with the ThetaProbe. Moisture measurements and container mass were measured every other day during a 33 day period. After the 33 day dry down, the substrate was oven-dried at 85°C for 2 weeks to determine the mass of substrate in each container. Volumetric moisture content from the balance was determined by taking the total weight of the container, substrate, and water minus the weight of the container and substrate which yielded the mass of water on each day. Water mass was converted to volume and divided by the volume of the substrate to give volumetric moisture content.

Regression analysis was performed and correlation between the ThetaProbe and balance volumetric moisture contents was best fitted to a 2nd order polynomial equation with an R^2 value of 0.8934, although the linear equation had an R^2 value of 0.8665. This moisture curve is similar in appearance to the generalized moisture curve for organic soils found on page 9 of the ThetaProbe User Manual (Anon., 1999).

Figure 1 shows the correlation between moisture content measured with the ThetaProbe and the moisture content determined from the balance during the dry down.

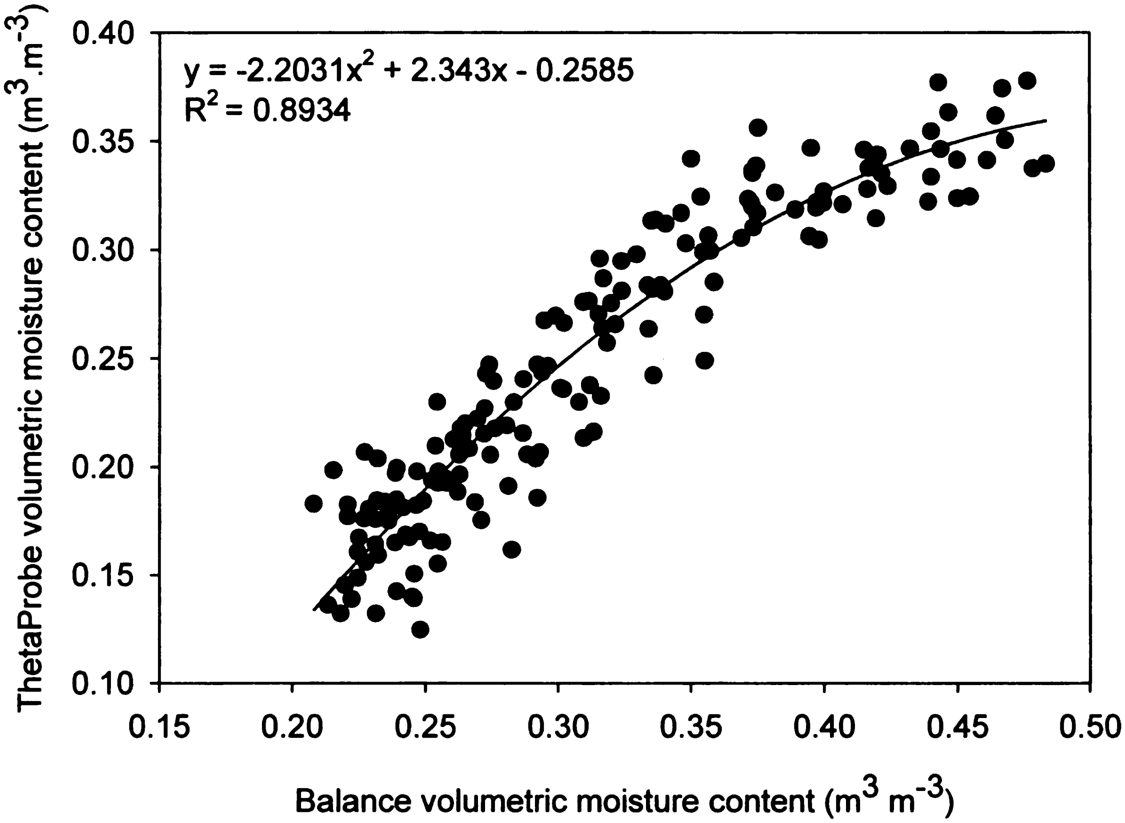

Figure AA1. Relationship between volumetric moisture content measured with a mass balance and a ThetaProbe moisture sensor of 85% pinebark:15% peat moss (vol:vol) potting substrate during a 33 day dry down in #3 nursery containers without plants. For the ThetaProbe measurements each data point is the mean of three ThetaProbe measurements·container^{-1}. Measurements were made every other day during the dry down from 10 containers.

Volumetric moisture content measured by the ThetaProbe was on average 0.11 $m^3 \cdot m^{-3}$ lower than volumetric moisture content measured using the balance.

This likely results from the top 60 mm of the container drying down faster than the lower portion of the container, which extended to a depth of 240 mm, due to drainage and surface evaporation. The experiments conducted during 2006 and 2007 required the measurement of volumetric moisture content from 180 plants and 720 plants when all plants were measured. This number of measurements and the additional labor and time required in taking this quantity of measurements from a greater depth in the substrate did not make measuring substrate moisture content at a greater depth in the container substrate feasible. Because the ThetaProbe was not left in-situ, making measurements at a greater depth in the substrate would have disturbed the substrate and created a hole where media was excavated to insert the ThetaProbe housing. This hole would have likely increased drainage through this portion of the container and possibly lead to a higher moisture content at the bottom of this hole where the rods would have been inserted than at the same depth elsewhere in the container. In addition, the convenience of measurement from inserting the probe directly from the surface would be more likely to be adopted by growers for use.

Literature Cited

Anonymous. 1999. ThetaProbe soil moisture sensor. User Manual ML2-UM-1.21. Delta-T Devices Ltd. Cambridge, England.

Gaskin, G.J. and J.D. Miller. 1996. Measurement of soil water content using a simplified impedance measuring technique. J. Agr. Engineering Res. 63:153 – 160.

Hanson, B.R. and D. Peters. 2000. Soil type affects accuracy of dielectric moisture sensors. California Agriculture. 54(3):43 – 47.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content. Water Resour. Res 16(3):574 – 583.

Whalley W.R. 1993. Considerations on the use of time-domain reflectometry for measuring soil water content. J. Soil Sci. 44:1 – 9

White I., J.H. Knight, S.J. Zegelin, G.C. Topp. 1994. Comments on 'Considerations on the use of time-domain reflectometry for measuring soil water content' by W.R. Whalley. J. of Soil Sci. 43:1 – 3.

APPENDIX B

ADDITIONAL TABLES AND FIGURES

Table AB1. Foliar nutrient content of container-grown *Hydrangea arborescens* 'Dardom' under four irrigation regimes on Day 48 and 92 (Chapter 1).

Nutrient	Control[z]	Foliar Nutrient Content 100DWU	100-75	100-75-75	Recommended Range[y]
Day 48					
Ca (%)	2.14	1.85	1.68	1.69	0.5 – 2.5
Mg (%)	0.84	0.59	0.65	0.63	0.3 – 1.0
Na (%)	0.01	0.01	0.01	0.01	na
S (%)	0.13	0.14	0.14	0.16	na
Fe (ppm)	658.00	224.00	173.00	210.00	50 – 300
Zn (ppm)	47.00	46.00	53.00	52.00	30 – 75
Mn (ppm)	159.00	134.00	176.00	172.00	30 – 300
Cu (ppm)	4.00	4.00	4.00	4.00	6 – 40
B (ppm)	44.00	38.00	37.00	37.00	30 – 50
Al (ppm)	18.00	14.00	15.00	9.00	na
Day 92					
Ca (%)	2.16	2.07	2.20	2.12	0.5 – 2.5
Mg (%)	0.89	0.86	0.63	0.66	0.3 – 1.0
Na (%)	0.01	0.01	0.01	0.01	na
S (%)	0.10	0.09	0.10	0.11	na
Fe (ppm)	906.00	516.00	368.00	438.00	50 – 300
Zn (ppm)	43.00	45.00	38.00	42.00	30 – 75
Mn (ppm)	99.00	192.00	144.00	162.00	30 – 300
Cu (ppm)	6.00	5.00	4.00	4.00	6 – 40
B (ppm)	42.00	39.00	40.00	39.00	30 – 50
Al (ppm)	22.00	24.00	30.00	26.00	na

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]General recommended range of foliar nutrient content for woody plants from: Plank, C.O. 2008. Plant Analysis Handbook of Georgia. The University of Georgia. College of Agricultural and Environmental Sciences. Cooperative Extension Service. Webpage: http://aesl.ces.uga.edu/publications/plant/index.htm Accessed: 04/23/2008

Table AB2. Foliar nutrient content of container-grown *Spiraea fritschiana* 'Wilma' under four irrigation regimes on Day 48 and Day 92 (Chapter 1).

Nutrient	Control[z]	100DWU	100-75	100-75-75	Recommended Range[y]
	Foliar Nutrient Content				
Day 48					
Ca (%)	1.09	0.92	1.14	1.12	0.5 – 2.5
Mg (%)	0.55	0.50	0.63	0.64	0.3 – 1.0
Na (%)	0.01	0.01	0.01	0.01	na
S (%)	0.13	0.14	0.14	0.14	na
Fe (ppm)	265.00	113.00	134.00	117.00	50 – 300
Zn (ppm)	62.00	72.00	74.00	82.00	30 – 75
Mn (ppm)	1452.00	2029.00	2272.00	3095.00	30 – 300
Cu (ppm)	4.00	6.00	5.00	5.00	6 – 40
B (ppm)	44.00	42.00	40.00	41.00	30 – 50
Al (ppm)	4.00	3.00	3.00	5.00	na
Day 92					
Ca (%)	1.55	1.37	1.35	1.28	0.5 – 2.5
Mg (%)	0.82	0.65	0.70	0.72	0.3 – 1.0
Na (%)	0.01	0.01	0.01	0.01	na
S (%)	0.10	0.10	0.11	0.11	na
Fe (ppm)	686.00	318.00	246.00	234.00	50 – 300
Zn (ppm)	57.00	53.00	58.00	59.00	30 – 75
Mn (ppm)	1689.00	1931.00	2021.00	2283.00	30 – 300
Cu (ppm)	5.00	8.00	7.00	5.00	6 – 40
B (ppm)	41.00	39.00	39.00	42.00	30 – 50
Al (ppm)	14.00	13.00	17.00	13.00	na

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]General recommended range of foliar nutrient content for woody plants from: Plank, C.O. 2008. Plant Analysis Handbook of Georgia. The University of Georgia. College of Agricultural and Environmental Sciences. Cooperative Extension Service. Webpage: http://aesl.ces.uga.edu/publications/plant/index.htm
Accessed: 04/23/2008

Table AB3. Foliar nutrient content of container-grown *Vibumum* × *burkwoodii* 'Chenaultii' under four irrigation regimes on Day 48 and Day 92 (Chapter 1).

Nutrient	Control[z]	100DWU	100-75	100-75-75	Recommended Range[y]
	Foliar Nutrient Content				
Day 48					
Ca (%)	1.39	1.43	1.36	1.40	0.5 – 2.5
Mg (%)	0.52	0.53	0.51	0.50	0.3 – 1.0
Na (%)	0.01	0.02	0.01	0.01	na
S (%)	0.19	0.22	0.18	0.18	na
Fe (ppm)	1150.00	620.00	550.00	459.00	50 – 300
Zn (ppm)	38.00	39.00	36.00	35.00	30 – 75
Mn (ppm)	77.00	100.00	77.00	86.00	30 – 300
Cu (ppm)	8.00	7.00	5.00	5.00	6 – 40
B (ppm)	42.00	43.00	41.00	42.00	30 – 50
Al (ppm)	19.00	22.00	26.00	16.00	na
Day 92					
Ca (%)	1.21	1.25	1.17	1.19	0.5 – 2.5
Mg (%)	0.51	0.55	0.48	0.47	0.3 – 1.0
Na (%)	0.01	0.01	0.01	0.01	na
S (%)	0.13	0.15	0.13	0.14	na
Fe (ppm)	1106.00	294.00	304.00	334.00	50 – 300
Zn (ppm)	32.00	57.00	40.00	46.00	30 – 75
Mn (ppm)	73.00	120.00	80.00	92.00	30 – 300
Cu (ppm)	4.00	5.00	3.00	2.00	6 – 40
B (ppm)	48.00	54.00	48.00	52.00	30 – 50
Al (ppm)	12.00	15.00	15.00	11.00	na

[z]Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 application cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

[y]General recommended range of foliar nutrient content for woody plants from: Plank, C.O. 2008. Plant Analysis Handbook of Georgia. The University of Georgia. College of Agricultural and Environmental Sciences. Cooperative Extension Service. Webpage: http://aesl.ces.uga.edu/publications/plant/index.htm Accessed: 04/23/2008

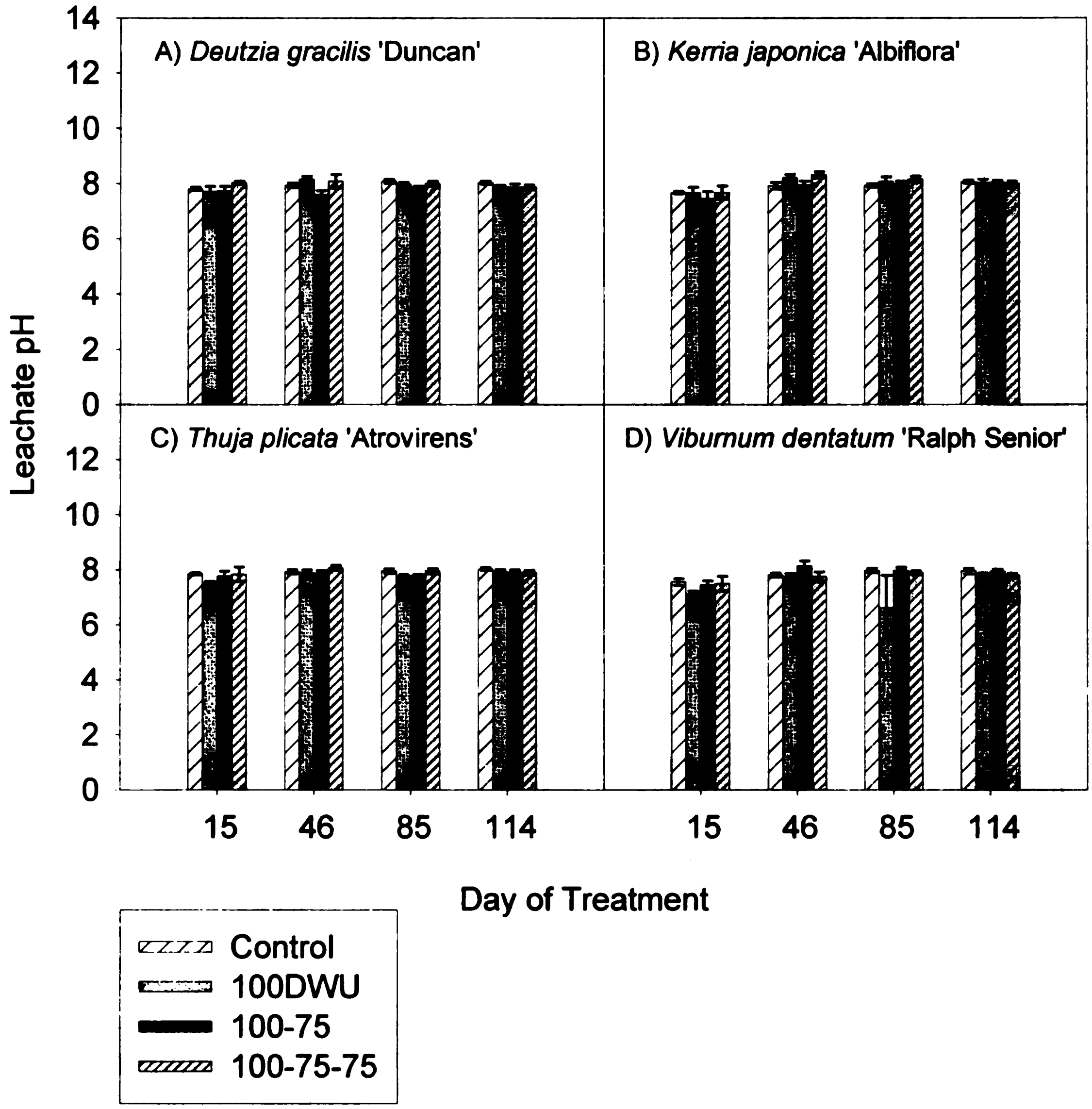

Figure AB1. Leachate pH of 4 container-grown woody ornamentals under 4 irrigation treatments applied from 8 June (Day 1) to September 31 (Day 115) 2007 (Chapter 2). Error bars represent standard errors of treatment means (n = 6).

Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 day cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU. DWU applied at highest DWU of 4 species on each sample day.

Table AB4. Means of daily maximum, daily minimum, and daily mean substrate volumetric moisture content of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' under 4 irrigation treatments from 8 June to 13 October 2007. Volumetric moisture content was measured in the top 6 cm of substrate. Measurements were made every one minute, and 15 minute means recorded and used to calculate daily means (Chapter 3).

Treatment	Rep	Substrate Volumetric Moisture Content (mc)		
		mc max. ($m^3 \cdot m^{-3}$)	mc mean ($m^3 \cdot m^{-3}$)	mc min. ($m^3 \cdot m^{-3}$)
Control^z				
	1^y	0.396 b^x	0.309 b	0.283 b
	2	0.503 a	0.399 a	0.377 a
	3	0.450 a	0.405 a	0.388 a
100DWU				
	1	0.479 a	0.316 a	0.281 b
	2	0.425 b	0.327 a	0.310 a
	3	0.470 a	0.312 a	0.289 ab
100-75				
	1	0.496 a	0.324 a	0.291 ab
	2	0.453 b	0.329 a	0.305 a
	3	0.410 c	0.297 b	0.277 b
100-75-75				
	1	0.448 b	0.299 b	0.277 b
	2	0.513 a	0.371 a	0.348 a
	3	0.374 c	0.294 b	0.272 b

^{z}Control = 19 mm-ha·application^{-1}; 100DWU = 100% daily water use (DWU) per application; 100-75 = 2 day cycle with 100% DWU first application and 75% DWU second application; and 100-75-75 = 3 application cycle 100% DWU the first application followed by two applications of 75% DWU.

^{y}Each treatment replicate represents a single container in a separate irrigation zone.

^{x}Means with the same letter within the same column within the same treatment are not significantly different (α = 0.05), n = 384. Means separation by Tukey's test (α = 0.05).

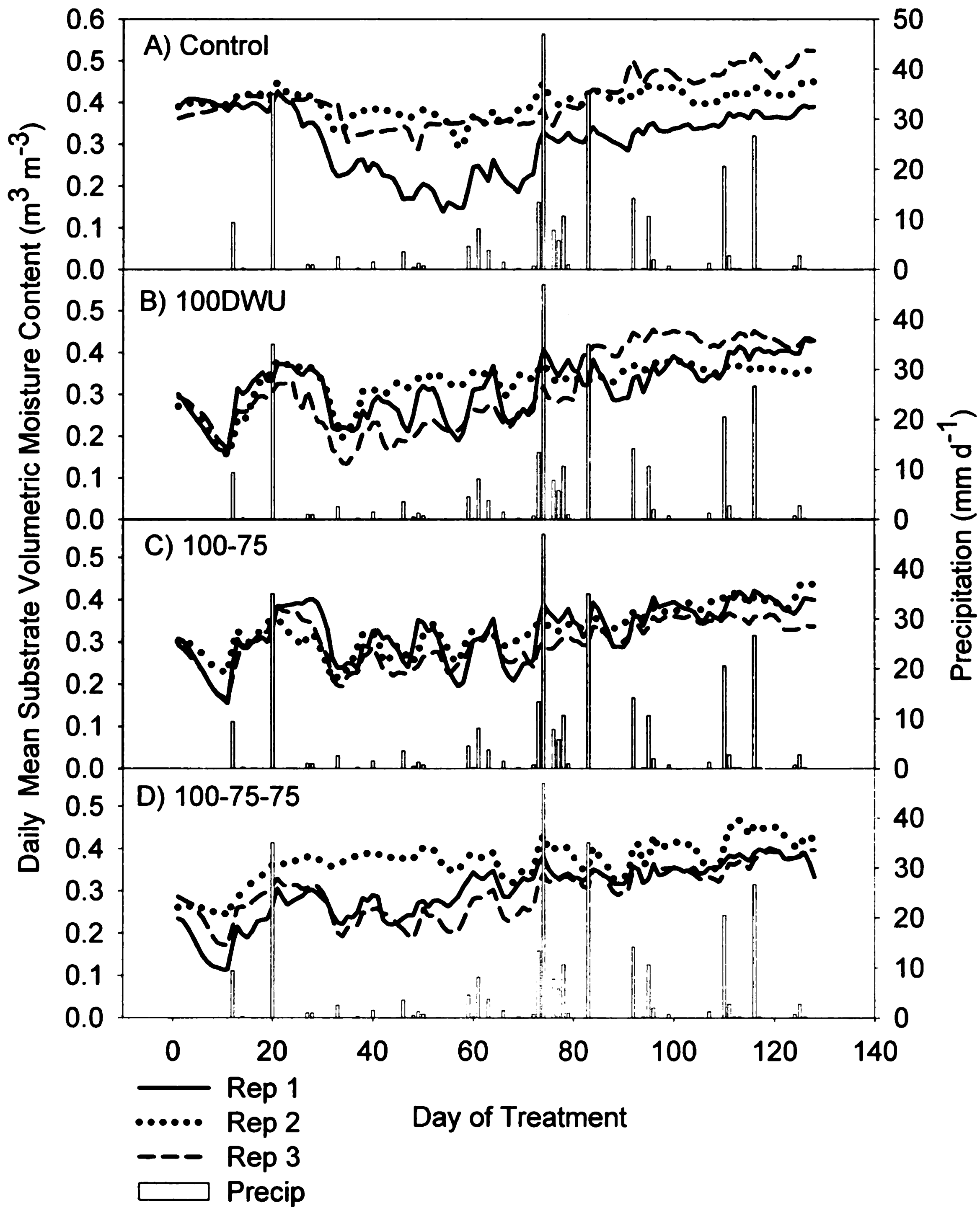

Figure AB2. Daily mean substrate volumetric moisture content (lines) of 10.2 L container-grown *Spiraea fritschiana* 'Wilma' under 4 irrigation treatments (A -D). Daily means calculated from 15 minute averages with measurements made every one minute using soil moisture sensors. Each rep corresponds to one container. Day 1 = 8 June 2007 and Day 128 = 13 October 2007. Vertical bars represent daily precipitation and correspond to the y-axis on the right (Chapter 3).