REDUCING WATER USE, RUNOFF VOLUME, AND NUTRIENT MOVEMENT FOR CONTAINER NURSERY PRODUCTION BY SCHEDULING IRRIGATION BASED ON PLANT DAILY WATER USE

By

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ABSTRACT

REDUCING WATER USE, RUNOFF VOLUME, AND NUTRIENT MOVEMENT FOR CONTAINER NURSERY PRODUCTION BY SCHEDULING IRRIGATION BASED ON PLANT DAILY WATER USE

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Daily water use (DWU) was used in two irrigation studies over two seasons to schedule irrigation. Plant DWU was determined from the difference in substrate volumetric water content over a 24 h period as measured using soil moisture sensors. Each year, irrigation was applied daily to container-grown shrubs in four treatments: 1) control application of 19 $mm{\cdot}ha^{-1}{\cdot}d^{-1}$, 2) irrigation applied to replace 100% DWU (100DWU) each day, 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle (100-75), and 4) a 3-day application cycle replacing 100% DWU the first day and 75% DWU on the second and third days (100-75-75). The objectives between the two studies were to 1) determine whether irrigating with DWU can save water compared to a control (time-based application) rate without affecting growth of ornamental shrubs and 2) classify each taxon into irrigation functional groups (IFG). Most taxa in DWU treatments received less water than the control, yet only growth index of one taxa was negatively affected by deficit irrigation applications. Additionally, an objective of the second study was to quantify runoff volume and nutrient content from production areas irrigated under the same irrigation treatments. Effluent volumes and NO_3^- -N and PO_4^{3-}-P loads from DWU treatments were reduced compared to the control. Consequently, irrigating based on DWU also reduced NO_3^- -N and PO_4^{3-}-P losses and improved %P and %K foliar concentrations compared to the control.

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Introduction

Agriculture is the largest consumer of our planet's water resources (O'Neil and Dobrowolski, 2011), and ornamental plant nurseries use some of the highest water inputs on an area basis of any agricultural sector. Container-grown crops now comprise over half of all ornamental plants sold today (Hodges et al, 2008), and they require frequent, if not daily irrigation due to the limited volume for water storage in the rooting substrate (Warren and Bilderback, 2004). Since most nurseries are located on the periphery of population centers, the conflicting interests between agriculture and urbanization often means nurseries have reduced access to water resources (Beeson et al, 2004).

One way to reduce nursery irrigation water inputs is to improve the efficiency of irrigation scheduling. Inefficient or uninformed irrigation scheduling can increase both water withdrawals and nutrient losses via runoff, which can move offsite to contaminate surrounding water sources. Improvements in irrigation scheduling can help improve water conservation at nurseries (Tyler, et al., 1996), timing and availability of water to plants for optimum growth (Warren and Bilderback, 2004), and nutrient and pesticide management to reduce loading in effluent (Warsaw, et al., 2009b).

Fundamental Importance of Water in Plants

Water is essential for plant growth and maintenance. In actively-growing tissues, water comprises 80-90% of fresh weight (Kramer and Boyer, 1995). Water is the universal solvent through which gases, salts, and dissolved nutrients and other compounds move throughout the plant (Kramer and Boyer, 1995). It is also responsible for maintaining cell turgor (Kozlowski and Pallardy, 2002), promoting cell enlargement (Kramer and Boyer, 1995), and regulation of the stomatal mechanism (Chaves et al., 1991). Water is the reagent in the photosynthetic reaction responsible for donating electrons for the synthesis of ATP (Pallardy, 2008). Consequently, a water deficit within plants negatively impacts the ability to photosynthesize and produce new biomass (Hsiao, 1993).

Water moves in plants along gradients from high potential energy to low (Pallardy, 2008). This gradient is responsible for the movement of water from the soil, where water exists at a higher potential energy state than the roots (when soil moisture is not limiting), into the roots and through stems to the leaves. In the leaves, water is either used for carbon assimilation during photosynthesis or transpired to maintain the water column (Kramer and Boyer, 1995). The cohesion-tension theory explains how this continuous water column is maintained in plants. As transpired water evaporates from stomata, a reduction in the water potential at the stomata draws water from within the leaf to replace that which has just evaporated. Because of the high cohesive forces of water, this action lowers the water potential within the xylem creating enough tension on the system to move the entire water column in the direction of transpiration (Kramer and Boyer, 1995). This process is sometimes referred to as the soil-plant-atmospherecontinuum (SPAC), which refers to the unification of forces exerted on water throughout the system (Pallardy, 2008).

Evapotranspiration and the Diurnal Cycle

Evapotranspiration (ET) involves both the evaporation of water from soil or the rooting substrate and transpiration of water through stomata or other porous plant organs (Pallardy, 2008). ET can be determined for a single plant, or with more intense investigation, an entire plant system (Pallardy, 2008). While evaporation is a function of the physical environment surrounding a plant, transpiration is both regulated by biological processes within the plant and its interaction with the external environment. The rate of transpiration depends on a variety of environmental factors including net radiation, soil temperature, soil water status, vapor pressure deficit between the leaf interior and the free atmosphere, the density of the air, temperature, and wind speed (Pallardy, 2008). Physiological and morphological traits also contribute to transpiration including total leaf area, canopy architecture, leaf exposure to sunlight, regulation of the stomatal aperture, and the water absorption capacity of roots (Pallardy, 2008).

To achieve growth, plants must undergo a minimum (though not absolute) amount of transpiration, and some flexibility likely exists to varying degrees in the exact quantities of water that must be transpired by each species to achieve maximum growth (Beeson, 2006). During periods of darkness, the stomatal aperture generally only remains partially open. Under well watered conditions, stomata open progressively further from sunrise until reaching maximum evaporative demand for that day (Hsiao, 1993). Cohen et al. (1985) showed that after a brief delay following sunrise, the transpiration rate in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) increased with solar irradiance, then remained at a maximum rate for several hours into the afternoon before declining into the evening and nighttime hours. However, as soil moisture became depleted during prolonged drought of container-grown *Acer rubrum* L., stomatal closure reduced transpiration rates and ultimately growth (Bauerle et al., 2002). Midday transpiration rates and the proportion of leaves to roots was reduced in drought-stressed *Fraxinus velutina* Torr., *Koelreutaria paniculata* Laxm., *Quercus macrocarpa* Michx., and *Q. muehlenbergii* Englem. compared to unstressed trees (Balok and St. Hilaire 2002).

In addition, reductions in photosynthesis often accompany midday water stress. During late morning and afternoon hours, net photosynthesis and conductance was reduced midday in *Vitis vinifera* L. irrigated at 50% ET_A, compared to 100% ET_A (Williams and Araujo, 2002). Generally, as drought progresses, cumulative stress results in the inhibition of photosynthesis progressively earlier each day (Hsiao, 1993). Consequently, internal plant water deficits often lead to reduced carbon fixation and overall productivity. For example, production of bedding plants at continuously low substrate volumetric water content (SVWC) set points ($0.09 m^3 \cdot m^3$ and $0.15 m^3 \cdot m^3$) decreased gas exchange and leaf photosynthetic rate in bedding plants compared to higher set points (Nemali and van Iersel, 2008). Container-grown plants are especially vulnerable to daily moisture deficits, and irrigating during midday or afternoon hours, when transpiration is highest, yielded increased dry weight and CO_2 assimilation of *Cotoneaster dammeri* ‘Skogholm’ compared to pre-dawn irrigations (Warren and Bilderback, 2004). However, after imposing minor irrigation deficits, corresponding reductions in growth do not necessarily occur. Among 24 shrub taxa growing in containers, growth was only reduced in two species in treatments that alternated a 75% ET replacement with 100% every other day (Warsaw et al., 2009a). Consequently, at mild substrate moisture deficits, a substantial buffer against growth reductions exists for temperate, humid-climate shrubs.

Water Use Efficiency

One method to relate productivity through carbon assimilation to water use is by evaluating the water use efficiency (WUE) of a species over a temporal period of interest. The following equation has been used by Jarrell et al. (1983), Knox (1989), and Warsaw et al. (2009a and 2009b) to calculate WUE over the course of an entire production cycle for container-grown ornamental shrubs:

WUE = increase in plant size / volume of water applied.

In the above studies, irrigation applications were based on ET so that major changes in ET resulted in modified irrigation application volumes. Generally, Knox (1989) and Warsaw et al. (2009a and b) showed that as irrigation volume is decreased, WUE improves. While drought-tolerant species may once have been thought to have higher WUEs, Knox (1989) showed that *Juniperus horizontalis* Moench 'Wiltonii' had the lowest WUE compared to four flowering shrub species. The author suggested that the *Juniperus* species used water less efficiently than the flowering shrubs during periods of non-limiting soil water. Warsaw et al. (2009b) reported both growth index increase (GII) and WUE with irrigation treatments based on DWU was higher compared to conventional, rate-based control of 19 $mm \cdot container \cdot day^{-1}$. Species in their study with lower GII also showed lower WUE compared to species with higher GII. However, irrigation was applied only to meet the needs of the highest water users, which means that the species having a lower WUE were likely over-irrigated. Their findings reveal that when emphasis is placed on managing irrigation inputs to optimize WUE during crop production, water applications can be reduced without sacrificing plant growth.

Special Concerns Pertaining to Container-grown Plants

Over half of all ornamental plants sold by nurseries today are produced in containers (Hodges et al., 2008). By confining roots to a limited volume of soil, the container itself substantially reduces quantities of water that can be stored for plant needs between irrigations compared to field grown production systems. Growers favor container production because it offers both producers and consumers many advantages such as easier handling and shipping of individual plants, flexibility of production schedules, ease of display of the finished product, and increased consumer convenience (Ingram et al., 1993; Chen et al., 2001). In addition, container substrates provide flexibility by allowing growers greater relative ease of manipulation of water and fertility levels than with most mineral soils (Chen et al., 2001). Many horticultural substrates in use today were intentionally designed with a high proportion of macropores relative to field soils, resulting in higher air-filled porosity (AFP) (Drzal et al., 1999) to ensure that they drain quickly in the event of frequent or heavy rainfall in (Knox, 1989). However, in bark-based substrates, a high AFP limits plant available water (PAW) as compared to peat (Lea-Cox et al., 2011) or mineral soils (Drzal et al., 1999). Additionally, black or other dark-colored containers function as heat sinks

(Ruter, 1999) resulting in warmer rooting zones than traditional soils (Neal, 2010). Reductions in growth of *Syringa vulgaris* L. 'Monge' produced in containers relative to field soils were attributed to increased substrate temperatures (Neal, 2010), which have been shown to elevate plant water use (Garcia y Garcia et al., 2004). Consequently, producers of container-grown plants must irrigate frequently during the growing season, often multiple times daily. Knox (1989) suggests that some growers may take advantage of the forgiving nature of today's rapidly-draining container substrates by over-irrigating to safeguard against possible reductions in growth or quality. This approach could have negative impacts on crop quality and the environment. Therefore irrigation scheduling must be approached more quantitatively.

Irrigation Scheduling

Increasing competition for water resources between urban population centers, industry, and other agricultural sectors has led to water withdrawal policies in states such as California, Delaware, Florida, Maryland, Michigan, North Carolina, Oregon, and Texas (Fernandez et al., 2009). However, even if a region has ample water supplies, the quality of that water may not be acceptable for plant production (Beeson et al., 2004). Consequently, 44% of nurseries currently incorporate some sort of water conservation measures into their irrigation scheduling practices, while an additional 12% are interested in implementing new sustainable water management practices in the future (Dennis et al., 2010).

Irrigation scheduling is a decision-making process which requires the person making the decision to assess the volume of water lost across an entire crop, determine the volume of water to be replaced by irrigation, and activate irrigation to the crop for an appropriate amount of time so as to replace the desired volume. The goal of a typical irrigation cycle is to provide a plant with enough water to reach container capacity and meet its total water requirement until the next irrigation period while not providing so much that excessive water and nutrient leaching from the substrate occurs (Majsztrik et al., 2011). Additionally, irrigators may impose specific practices in order to meet certain goals such as cyclic irrigation to minimize mid-day water stress or management allowed deficit that ensures VWC never falls below a desired threshold. Ideally, irrigation blocks would consist of plants of similar water requirement.

Overhead irrigation systems involve the distribution of water through sprinkler emitters that cover a large area containing many container-grown plants using relatively few emitters. Overhead irrigation is almost exclusively used for 26.5 L (#7 trade-size) containers and smaller (Beeson et al., 2004). Generally, overhead systems require fewer labor hours for inspection than microirrigation systems because problems can be quickly identified and corrected (Beeson et al., 2004). These systems are desirable because they accommodate some variation in land topography while volume of water and its distribution can be easily regulated (Goodwin et al., 2003). Irrigation application efficiency (IAE) is the amount of water retained in the container substrate divided by the total water applied (Beeson and Knox, 1991). Since the longer an overhead system applies water, the longer water is being applied off target, an increase in container spacing results in lower IAE, particularly when small containers are spaced the same distance apart as larger containers (Beeson and Knox, 1991). One of the best ways to improve irrigation efficiency (IAE) with overhead systems is to irrigate only for the duration needed to supply adequate water to plants without causing a reduction in growth. Hence, the timing and volume of irrigation application is especially important when overhead irrigation systems are employed. For efficient irrigation of container-grown plants, need-based irrigation applications can be based on either a specific leaching fraction, estimation of crop ET using climactic models, or direct measurement of substrate moisture with a variety of sensors.

Traditional Approach

Historically, the primary technique employed in determining plant needs for scheduling irrigation of container plants simply involves decision-making based on a grower's experience (Warren and Bilderback, 2004). This process may involve visual or tactile assessments of plant canopies for losses in turgor, lifting a few representative containers to estimate weight, or the use of a "feel" test to gauge the overall dampness of rooting substrates. While these methods of irrigation scheduling may indicate that plants need water, they do not quantify the precise amount. It is probable that errors occur in the estimation of plant water needs as well. Additionally, many growers apply more water than is necessary as a safeguard against under- watering plants (Bauerle and Post, 2002). While some growers may feel that they are erring on the side of caution, numerous studies show that permitting moderate moisture deficit has little to no effect on growth (Warsaw et al., 2009 a and b ; Beeson, 2006; Groves et al., 1998; Tyler et al., 1996; Welsh and Zajicek, 1993; and Fitzpatrick, 1983). Furthermore, grower "intuition" or fixed-rate irrigation scheduling may increase crop losses due to disease (Chappell et al., 2013) and reduce growth of ornamental shrubs compared to quantitative approaches (Belayneh et al., 2013; Warsaw et al., 2009a; Million et al., 2007; Welsh and Zajicek, 1993). Higher irrigation volumes associated with fixed-rate scheduling also contribute to leaching of nutrients from containers making them unavailable for plant growth (Warsaw et al., 2009b).

Fain et al. (2000) surveyed 24 Alabama container nurseries about their irrigation management practices. The results showed that only 50%, 57%, and 33% of small (0.4-4.1 ha), medium (4.5-16.6 ha), and large (40+ ha) growers, respectively, test irrigation system efficiency. When asked how much water was normally applied, respondents indicated that, on average, irrigation was run for 1 h to apply 2.5 cm (1 in.) (Fare et al., 1992). However, the study determined that the actual amount applied by Alabama nurseries was only roughly 1.6 cm during each 1 h irrigation event- 40% less the growers intended. Additionally, Garber et al. (2002) reported that with each irrigation event, Georgia nurseries applied 2.5 cm to containers ranging from 3.8L to 11L in volume. Since the Georgia application rates were based on responses to surveys completed by nursery managers themselves, the application volumes determined from Georgia are best considered generalizations (Garber et al., 2002). Leaching fraction (LF) is often suggested as a method to schedule irrigation and can be determined with common nursery supplies using the following formula:

LF = volume of leachate water / volume of applied water (Tyler et al., 1996)

Irrigators are often advised to use the above to determine the required volume of water to apply to container-grown plants.

Warren and Bilderback (2005) indicate that irrigating to a LF of 0.0 would be ideal to replace the exact volume required necessary to restore the substrate to container capacity without any leaching from the container. Niemiera and Leda (1993) examined the effects of LF on total N leaching from PVC columns filled with pine bark substrate, without plants. A total of 140 mg N was applied from CRF, and at a leaching fraction of 0.4, 50.0 mg was recovered in leachate. Irrigating by low LF can reduce water applications and nutrient losses due to leaching. At a LF of 0.4, approximately 99% more total N applied to container substrates was leached than at a LF of 0.0 (Niemiera and Leda, 1993). These results strengthen the case Warren and Bilderback (2005) make for setting the target LF at 0.0 when scheduling irrigation. Irrigating at low LF can lead to buildup of salts in substrates, particularly with long-term crops such as woody ornamentals. Electrical conductivity (EC) is most commonly used to express the concentration of total soluble salts in a substrate or soil. Published guidelines for ideal EC ranges for medium to high-nutrient use nursery crops include 0.8-1.5 $dS \cdot m^{-1}$ and 1.0-2.0 $dS \cdot m^{-1}$ [Yeager et al., (2003), and Smith and Logos, (2008)]. A correlation was shown between EC and NO_3^--N concentrations as they fluctuate over a growing season in *Ilex cornuta* Lindl. & Paxt. 'Burfordii' (Ruter, 1992). Because this correlation exists, EC is commonly used as an indicator of substrate nutrient status. Generally, greater quantities of nutrients are available at a higher EC than at a low EC under a normal fertilization regime. Therefore, EC should be routinely checked during production of container plants, particularly in salt sensitive plants, and leached when recommended maximum levels are reached to avoid the incidence of salt injury.

Approaches Involving Modeling of Evapotranspiration

Many approaches to irrigation scheduling involve making an estimate or direct measurement of ET to determine water needs of a particular crop in order to conserve water. Estimates of ET are usually based on the equation developed by Thornthwaite in 1944:

$$ET_A = ET_0 \times K_C.$$

where ET_A represents actual evapotranspiration of the crop, ET_0 represents the potential evapotranspiration of a reference crop, and K_C is a crop-specific coefficient derived for the crop. ET_A can be derived in any one of several ways by: 1) conducting an energy-balance analysis from published weather history and K_C values; 2) relation of crop yield to ET_A; 3) direct measurement followed by a water-balance method and 4) directly measuring water use of the crop using a lysimeter or with a variety of soil moisture sensors available today (Burt et al., 1997). The ET_0 is the estimated transpiration specifically derived for a healthy, actively-growing, unshaded, and well-watered reference crop maintained at a height of 8 - 15 cm, usually turfgrass (Doorenbos and Pruit, 1975). The equation considers solar radiation, temperature, relative humidity, and wind speed using a derivative of the Penman-Monteith equation (Monteith, 1964; Penman, 1948). Finally, K_C is determined from experimental observation of the crop's total ET_A usually over an extended period, which is then divided by the total ET_0 from the same period.

Relation of Evapotranspiration to Crop Yield

In ornamental plants, yield is most often expressed as a growth parameter such as growth index, canopy volume, wet or dry shoot or root weight, or canopy closure. Water use has been positively correlated with potential evapotranspiration and growth index when estimated using either the Thornthwaite equation (R^2=0.49 - 0.81) or pan evaporation (R^2=0.78 - 0.88) (Knox, 1989). In another study, both canopy dry mass and final growth index were linearly related to ET_A and highly correlated in *Viburnum odoratissimum* Ker.-Gawl., *Ligustrum japonicum* Thunb., and *Rhaphiolepis indica* Lindl (Beeson, 2006). Beeson (2010) has since developed a simpler equation requiring only the input of container spacing once per crop rotation, canopy width every 3 weeks to determine percent canopy closure (a growth parameter), and daily ET_0 values to determine a water needs index (WNI). Percent canopy closure was exponentially correlated to WNI (average weekly ET_A : average weekly ET_0) with an r^2 of 0.868 (P = 0.001). Early in production, a high WNI was attributed to high evaporation rates resulting from minimal canopy closure (6-12%). But as closure increased, transpiration accounted for an increasing percentage of measured ET_A, and the model began responding more directly to changes in ET_0. Since most nurseries already perform regular growth measurements to track crop progress, the percent closure model presents a means to relate these simple growth parameters to ET_0 for precision irrigation scheduling (Beeson, 2010).

Energy Balance Method Using Crop Coefficients

Since K_C's were initially developed for use with field-grown agronomic crops whose unrestricted roots are assumed to extend to the edge of each plant's canopy, adaptation to container-grown nursery stock should consider the small surface area of substrate (relative to the plant canopy) within the container exposed to the atmosphere. Burger et al (1987) used the following equation to calculate K_C for container plants:

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

Overall, the number of K_C values developed for container-grown nursery crops is quite limited considering the thousands of species and cultivars produced in ornamental horticulture (Irmak, 2005). Where field-grown crops are generally assumed to have a soil water reservoir extending to the edge of their canopies, canopies of container crops may extend several times beyond container surface area, which thereby limits rooting volume and evaporative surface area within the container (Burger et al., 1987). Therefore, where field crops rarely exceed K_C values of 1.0, container-grown ornamentals may exceed 5.0 (Burger et al, 1987; Warsaw et al, 2009a). Beeson (2005) and Irmak (2005) note that the development of K_C values for nursery crops is a time-intensive undertaking considering the thousands of woody ornamental cultivars in production. Furthermore, Schuch and Burger (1997) reported that their K_C values developed for woody shrubs in southern California were less useful in winter than summer and varied by site. Also, K_C values in five of the twelve taxa did not adequately approximate ET_A for the reliable scheduling of irrigation; instead they suggested that high water use taxa would benefit from more frequent adjustments of K_C values based on physiological development throughout the season or microclimate.

One study reported highly positive correlations between K_C values developed for *Viburnum odoratissimum* and weeks after transplant, plant growth index, cumulative ET_0, and fraction of thermal units ($R^2 \geq 0.93$) (Irmak, 2005). While these variables are all less intensive to measure than ET_A directly, models relying upon plant growth rate may require the development of separate K_C values for different seasons (fall growth patterns were linear rather than exponential as in summer), phenological development, or container spacing. As an alternative to using growth rates, normalization of ET_A by canopy area has shown a strongly negative correlation with K_C ($R^2 = 0.951$) (Beeson, 2004). During validation, this model demonstrated a 410 mm reduction in irrigation inputs compared to plants irrigated with manually-activated irrigation that was manually scheduled based on observation of weather trends (Beeson and Brooks, 2008). Plants irrigated using the model also reached saleable size three weeks sooner than those irrigated by irrigator intuition (Beeson and Brooks, 2008). Since K_C values were related to canopy closure, an additional advantage of this modeling approach is that, theoretically, the model is not dependent on container size and spacing or season provided that canopy closure remains constant between meteorological seasons (Beeson, 2005). Overall, several elements associated with using models to predict ET_A

of woody ornamentals are still not fully understood such as the frequency with which measurements of plant growth should be collected or the effects of canopy shedding in relation to canopy closure (Beeson, 2005). Additionally, models will probably (at a minimum) need to be developed for representative species in each of the irrigation functional groups (IFG) proposed by Burger et al (1987) and then selectively applied to the 1000's of remaining taxa produced in ornamental horticulture today for which ET_A has not been intensively studied (Beeson, 2005).

Error commonly occurs in the use of ET_A- based models due to inaccurate yield data, variations between varieties of a particular species, or variation in ET_0 between the modeled year and subsequent years. At nurseries, plants growing in microclimates due to varying topography, crop canopies, surface albedos, or surrounding vegetation may perform differently than modeled plants. Additionally, faulty or poorly-calibrated instrumentation or improper use of equations to derive ET can also reduce model efficacy (Burt et al, 1997).

Soil Water Depletion Approach Using Sensors

This approach involves taking direct measurements of substrate water depletion in containers, which eliminates some of the assumptions made when using modeling to determine ET_A. Methods in use include measuring gravimetric change, matric potential, and estimation of substrate volumetric water content (SVWC) from the dielectric constants of water in relation to those of substrate solids (van Iersel et al., 2013). In practice of measuring soil water depletion, a measurement is taken shortly after an irrigation event to establish a baseline moisture content to which the irrigator wishes to return with the next irrigation. Then, just before the next irrigation occurs, another measurement must be taken, so the differential between these two measurements is considered ET_A for that period of time. Alternatively, a pre-determined moisture level can be targeted as a set point for activation of irrigation to maintain substrate moisture above a certain level (Kim et al., 2011). Many researchers have used weighing lysimeters to gravimetrically determine SVWC in ornamental shrub taxa since they provide a direct measure of water lost to ET_A (Burger et al., 1987). Welsh et al (1991) used lysimeters to determine volumes that replaced 50%, 75%, and 100% of ET_A in *Photinia* x*fraseri* Dress. on either 3.5 d or 7 d intervals. Measurements of substrate matric potential can also be used to estimate plant water needs; much like SVWC measurement, users identify critical water potential set points based on water availability to plants. The target range for irrigation scheduling using horticultural growing substrates should be from 0 to -10 kPa (Lea-Cox et al, 2011). Within this range lie two important parameters: EAW (easily-available water; ≈-5.25 kPa) and WBC (water buffering capacity; ≈-10.25 kPa). The bulk of water available for plant growth lies in the EAW range whereas WBC functions to signal that irrigation is required in order to avoid compromising growth (Lea-Cox, 2011). For 80% pine bark : 20% peat moss (vol:vol) substrate, Lea-Cox et al (2011) reported that 40.0% of total water at CC is EAW while the WBC consists of just 7.0% total water. Rose et al (1999) grew *Acer* x*freemanii* E. Murray ‘Jeffersred’ and *Malus* x*zumi* (Rehd.) ‘Calocarpa’ at 5 kPa and 18 kPa tension setpoints. Plants subjected to the high moisture tension treatment showed reduced whole-plant dry weight, shoot length, and leaf area for both taxa compared to the low tension treatment.

Dielectric sensors are frequently used when estimating moisture in horticultural substrates and are based on readings of the dielectric permittivity of the materials in the substrate. The basis of this technology relies on the differentials between the dielectric constants of the different media components into which an electrical current is discharged. The higher the dielectric constant, the better the substance's ability to conduct the charge. Water, with a dielectric constant of ≈80 (at 20^{o}C), is distinctly higher than air (≈1), mineral soil particles (≈4) (Campbell et al, 2007), or organic substrate constituents such as peat (2.31) and pine bark (2.66) (Naasz et al., 2005). Since the bulk of the signature will originate from substrate water, it can be related to SVWC.

Dielectric sensors use two basic technologies. First to be introduced was the time domain reflectometer (TDR). This type of sensor consists of two or more metal rods that determine permittivity by analyzing the duration needed for an electromagnetic wave to pass out of one rod, through the substrate, and back through another rod into the receiving unit (Bittelli, 2011). TDR's are especially useful because the rods can be cut to a wide range of lengths to suit a variety of applications. Permittivity is averaged over the entire length of the rod. Thus, the longer the rod, the greater is the depth over which permittivity is integrated at the expense of resolution within the sampled profile. However, increasing levels of EC in the soil sample reduce the accuracy of TDR (Campbell et al, 2007). A frequency domain reflectometer (FDR), also known as a capacitance sensor, differs from TDR in that it produces a voltage that passes through the substrate (which acts as a resistor) and continues oscillating that voltage until the strongest resonating frequency is found. This reflects the dielectric constant, and, in turn, the substrate water content (Greenwood et al, 2009). Capacitance sensors are more economical than TDR, which makes them ideal for deployment in large numbers, but they are slightly less accurate (Campbell et al, 2007). High EC can also skew capacitance readings, but sensors are available today that are minimally affected by changes in EC up to 10 $dS{\cdot}m^{-1}$ (Campbell et al, 2007).

Many moisture sensors are available today that can be used to estimate irrigation needs with reasonable precision in container nursery substrates. Dataloggers can be equipped to read hundreds of moisture sensors and even use relays for automated switching of irrigation control valves to create a fully-automated irrigation system driven by plant demand (Cornejo et al, 2005; Nemali and van Iersel, 2006; Burnett and van Iersel, 2008). In these systems, SVWC is usually permitted to fall to a certain level (though above a level that would induce stress), before irrigation restores the substrate to CC.

One of the most extensive studies using soil moisture sensors to determine water use in container-grown ornamentals was conducted by Warsaw et al (2009a). The researchers used a single hand-held TDR probe to collect SVWC data then calculated DWU and scheduled irrigation to replace only that water lost to DWU. When subjected to an irrigation control of 19 $mm{\cdot}ha^{-1}{\cdot}d^{-1}$, three species were smaller in their respective controls at the end of the production season than those irrigated to replace 100% of their DWU. Among the 24 shrub taxa sampled, water savings in DWU-based treatments ranged from 6% to 75% compared to their control (Warsaw et al., 2009a).

Manually measuring SVWC across many plants to determine DWU was a drawback of this system, and as such, it was not practical to take DWU measurements daily throughout the study. Consequently, DWU was calculated and irrigation volumes adjusted at 10-14 d intervals (Warsaw et al., 2009a). Although the authors took new DWU measurements anytime they perceived major changes in weather patterns that may affect DWU, applying one DWU quantity over a protracted period still carries the risk of over- or under-estimating irrigation needs on individual days when environmental conditions and plant growth are invariably changing. Nevertheless, plants in DWU treatments still performed as well as their control.

Sensor-based Automated Irrigation Systems

Several systems have used dataloggers to control capacitance sensors and activate irrigation for entire production seasons in greenhouse crops based on predetermined SVWC set points (Kim et al., 2011; van Iersel et al., 2010; Burnett and van Iersel, 2008). Using one of these systems, stem length increased with increasing SVWC set point in *Gaura lindheimeri* Engelm. & Gray ‘Siskiyou Pink’ (Burnett and van Iersel, 2008) and *Petunia* x*hybrida* (Kim et al., 2011). Where overhead irrigation is used at container nurseries, set point systems may not be easily integrated into their production. Under this scenario, set points could activate irrigation at any time throughout the workday, thereby surprising unsuspecting workers and forcing them to relocate outside the active irrigation zone until irrigation ceases. Unpredictable irrigation events could also inadvertently wash away pesticides before achieving their desired effects or cause increased foliar diseases resulting from extended periods of foliage wetness.

Lea-Cox et al. (2013) described a wireless sensor network that includes a control node capable of reading up to five capacitance sensors and provides control function for one irrigation solenoid. This offered growers a rapidly-deployable system with wireless nodes that can transmit data over distances greater than 1 km enabling growers to connect all parts of a nursery to the same network without wires. The system also had the ability to monitor substrate temperature, EC, rainfall, irrigation water applications, air temperature, relative humidity, and photosynthetically active radiation at 15 min resolution. A user-friendly interface has now been developed integrating real-time data views, configurable charts, irrigation control, online access, alerts, and plant models (Kohanbash et al., 2013). A system consisting of 40 sensors, eight nodes, computer, base station, and software was assembled in 2011 for $10,310 (USD) (Lichtenberg et al., 2013). The system nearly halved production time of *Gardenia augusta* 'MADGA 1', reduced losses due to foliar diseases, and increased overall profitability 119%. Using similar hardware, Belayneh et al. (2013) reduced water applications to medium and high water use landscape tree species by 63% and 34% in a pot-in-pot operation compared to a control irrigation schedule based on actual grower practice.

Given the expense, infrastructure modifications, and time required for nurseries to adopt wireless sensor networks, nurseries will not likely be able to directly monitor each of their hundreds of ornamental crops for irrigation scheduling (Lea-Cox et al., 2013). Until more water use information is developed, representative, or "indicator" crops, can form the basis for grouping plants of into "irrigation functional groups" (IFG) (as by K_C; Warsaw et al., 2009a) to appropriately assign them to irrigation blocks (Yeager et al., 2003). It should also be noted that although many manufacturers claim that their systems are “plug-and-play”, all dielectric sensors benefit from calibration to the specific substrate (van Iersel et al., 2013). Logically, incorrectly-calibrated sensors could result in gross under- or over-approximation of plant water needs. Also, during sampling, a disturbance of sensor-soil contact could result in inaccurate readings (Burt et al, 1997).

Regulatory Policies on Agricultural Water Quality and Nutrient Content

In addition to being high users of water for irrigation, nurseries can also be sources of non-point pollution if NO_3^--N and PO_4^{3-}-P are allowed to escape from production areas into the surrounding environment (Sharma, et al., 2008). The environmental impacts of both of these nutrients are coming under more intensive legislative scrutiny, which could become a major issue for container nurseries (Sharma et al., 2008). The U.S. legal NO_3^--N threshold for safe drinking water is 10 $mg \cdot L^{-1}$ (USEPA, 1986). Sharma and Bolques (2007) sampled runoff water from two container production nurseries to analyze NO_3^--N and PO_4^{3-}-P concentrations. While levels were much higher in containment areas onsite, outflow concentrations into natural surface waters were 8 $mg \cdot L^{-1}$ NO_3^-- N and 5 $mg \cdot L^{-1}$ PO_4^{3-}-P. These levels are below the USEPA threshold for drinking water safety but the Michigan Department of Environmental Quality (MDEQ) reports that just 0.3 $mg \cdot L^{-1}$ PO_4^{3-}-P may promote cyanobacteria blooms in surface waters (MDEQ, 2008).

In Section 132.2 of “Final Water Quality Guidance for the Great Lakes System”, the USEPA defines a TMDL as “the sum of the individual wasteload allocations for point sources and load allocations for nonpoint sources” (USEPA, 1995). The purpose of a TMDL is to set a maximum tolerable rate at which pollutants can be added to a water body on a case-specific basis (USEPA, 1995). Although the severity of TMDL regulation varies by watershed, the Chesapeake Bay is one of the most noteworthy cases because its legislation affects six states. Current NO_3^--N and PO_4^{3-}-P deposition rates for the bay are approximately 60% and 50% above the guidelines mandated by the EPA (CBF, 2010). Since acreage of agricultural production has been shown to increase total nitrogen and NO_3^--N levels in surface waters (Jordan et al, 1997), the state of Maryland required almost all agricultural operations to draft their own management plans for nitrogen and phosphorus by the end of 2002 (Lea-Cox et al, 2001) in hopes that doing so would encourage growers to take steps that would reduce nutrient losses into the bay and other surface waters. In Florida, agriculture accounts for 98% of all phosphorus imports into the Lake Okeechobee watershed where the phosphorus TMDL of 40 $ug \cdot L^{-1}$ places agricultural nonpoint sources under intense scrutiny (FDEP, 2001). Another example of TMDL regulation is the state of Michigan’s restrictions on phosphorus levels in 12 watersheds throughout the state (Anonymous, 2011). Relatively few Michigan nurseries occur in close proximity to the areas regulated and no statewide regulations are in place for the concentration of PO_4^{3-}-P from nonpoint pollution sources at this time (PPAC, 2007). However, with several states restricting nutrient concentration (Beeson et al., 2004) or quantity (as with TMDL’s) leaving agricultural operations, many nurseries may have to reevaluate and modify current irrigation and fertilization practices in order to become compliant with forthcoming legislation.

Irrigation Management to Reduce Nursery Runoff

One of the most effective ways to reduce nutrient losses from nurseries is to reduce leaching from container substrates by means of proper irrigation scheduling (Majsztrik et al., 2011). Volume of water applied to *Cotoneaster dammeri* Schneid. 'Skogholm' growing in 3.8 L containers was reduced 44% under a low LF of 0.0 to 0.2 compared to a high LF of 0.4 to 0.6 while volume of effluent recovered from containers was reduced 63% (Tyler et al., 1996). A corresponding decrease of 66%, 62%, and 57% was observed in total NO_3^--N, NH_4^+-N, and P_2O quantities in effluent, respectively. Furthermore, excessive LF's may deplete available nutrients prematurely in the growing season, forcing either a second CRF application or sacrificed late-season growth (Mohammed et al. 2009).

Basing irrigation on ET_A of shrubs growing in 2.4 L containers versus a standard fixed rate of 10 $mm \cdot d^{-1}$ has been shown to reduce runoff volumes by 42% while total N and P losses were reduced 19% and 27% (Million et al., 2010). Warsaw et al. (2009b) showed runoff volume reductions of 66% and 79% under 100% and 75% DWU applications compared to their control application of 19 $mm \cdot d^{-1}$ for shrubs growing in 10.2 L containers. In addition, total quantities of NO_3^--N lost in the runoff were 38% and 59% lower than the control under 100% DWU and 75% DWU applications. Similarly, quantities of PO_4^{3-}-P lost in the runoff under 100% DWU and 75% DWU application volumes were 46% and 74% lower than the control volume (Warsaw et al., 2009b). The above research indicates that plant-based irrigation scheduling shows great promise in reducing nutrient losses from containers and subsequent nutrient loading from nurseries into the environment that contributes to non-point source contamination of surface waters.

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CHAPTER ONE

GROWTH, SEASONAL CROP COEFFICIENTS, AND NUTRITION OF CONTAINER-GROWN SHRUBS UNDER FULL AND DEFICIT DAILY WATER USE IRRIGATION TREATMENTS

Abstract

The study objectives were to: 1) determine whether irrigating with daily water use (DWU) can save water compared to a control, time-based, application rate in 14 shrub taxa without affecting growth 2) determine whether DWU irrigation reduces nutrient losses, and 3) classify shrubs into irrigation functional groups (IFG). During the experimental period of each year, irrigation was applied daily to 8 shrub taxa in four treatments: 1) control application of 19 $mm \cdot ha^{-1} \cdot d^{-1}$, 2) irrigation applied to replace 100% DWU (100DWU) each day, 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle (100-75), and 4) a 3-day application cycle replacing 100% DWU the first day and 75% DWU on the second and third days (100-75-75). In 2009, average DWU was highest for *Hydrangea paniculata* 'Limelight' in the 100DWU treatment at 17.3 $mm \cdot container \cdot day^{-1}$ and lowest for *Aronia arbutifolia* 'Brilliantissima' and *Thuja plicata* 'Grovepli' in the 100DWU treatment at 8.8 and 9.0 $mm \cdot container \cdot day^{-1}$. Most taxa received less water than the control, yet only growth index (GI) of *Hydrangea paniculata* 'Limelight' was affected with 100DWU plants finishing larger than the control. In 2010, average DWU for the season was highest in the 100-75 treatment for *Hydrangea arborescens* 'Abetwo' at 20.5 $mm \cdot container \cdot day^{-1}$ and *Hydrangea paniculata* 'Limelight' at 22.0 $mm \cdot container \cdot day^{-1}$. *Syringa* x*hyacinthiflora* 'Evangeline' required the least water of any taxa in the 100-75-75 treatment at 2.1 $mm \cdot container \cdot day^{-1}$. In every case, GI of DWU plants was equal to control plants except *Hydrangea*

paniculata 'Limelight' in the 100-75-75 treatment, which was smaller than the other treatments. Our results suggest that nurseries can use substrate moisture sensors to precisely schedule irrigation according to changing plant need and consequently reduce irrigation volume without affecting growth of most species.

Introduction

Irrigation efficiency can be improved with proper irrigation scheduling that also reduces water, nutrient and labor inputs. Because producers must irrigate container-grown nursery plants frequently, often multiple times daily, large water withdrawals made by nurseries often places them in competition for water resources with population centers, industry, and other agricultural sectors (Beeson et al., 2004). Besides increasing water withdrawals, inefficient irrigation scheduling also increases nutrient losses into runoff, which can move offsite to contaminate surrounding water sources. Irrigation should be scheduled to provide sufficient water to raise substrate moisture to container capacity while minimizing leaching to only that which is necessary (Majsztrik et al., 2011).

Belayneh et al. (2013) showed that sensor-controlled irrigation reduced water applications to medium and high water use landscape tree species by 63% and 34% in a pot-in-pot operation compared to a control irrigation schedule based on grower intuition. Additionally, Warsaw et al. (2009a and 2009b) demonstrated that irrigating according to plant daily water use (DWU) reduces water inputs while maintaining similar or improved growth versus a standard, time-based nursery irrigation schedule. Furthermore, when used to schedule irrigation, soil moisture sensors have recently been shown to reduce crop losses due to disease and increase profit for ornamental plant producers mainly by shortening plant production time (Lichtenberg et al., 2013). Sensor-based estimation of DWU has also resulted in decreased total quantities of NO_3^--N in effluent 38% and 59% in 100% DWU and 75% DWU applications compared to a standard irrigation rate (Warsaw et al., 2009b).

In this study, DWU was determined with both intermittent time domain reflectometry (TDR) samples and time capacitance sensors in real time for the application of three irrigation treatments. The objectives of this project were to 1) determine whether irrigating with daily water use (DWU) can save water compared to a control rate of 19 $mm \cdot ha^{-1} \cdot d^{-1}$ in 14 shrub taxa without affecting growth 2) determine whether DWU irrigation reduces nutrient losses, and 3) classify shrubs into irrigation functional groups (IFG). Plant growth index (GI) and dry weight, DWU, K_C, water use efficiency (WUE), leachate electrical conductivity (EC) and pH, and foliar nutrient concentrations were measured to compare effects of three DWU-based irrigation treatments to the control.

Materials and Methods

Site

The Michigan State University Horticulture Teaching and Research Center (HTRC), Holt, Mich., is located at latitude 42.67 degrees north, longitude -84.48 degrees west, and elevation of 264 m. Plants were grown on a site representative of a typical production nursery. Containers were placed on a level surface of limestone gravel with landscape fabric underlain at a 15 cm depth to reduce weed emergence. Production areas were 4.9 m x 7.3 m and spaced 0.3 m apart. A Michigan Enviro-weather station is located at the HTRC to monitor environmental conditions (MSU, 2011).

Irrigation System

Irrigation was activated in each production bed by a 1.9 cm diameter 24 V alternating current solenoid valve (various manufacturers). Irrigation nozzles (Pro-Spray®, Hunter Industries Incorporated; San Marcos, CA) were mounted on 1.3 cm diameter by 0.66 m high risers. The nozzles were spaced 2.44 m apart along the perimeter of each production area with all water directed inward. Four- 90° nozzles were positioned on the corners of the production area, two- 180° nozzles were positioned between the corner nozzles on each E-W perimeter, and one- 180° nozzle was placed on the N-S production area. Additionally, two- 360° nozzles were positioned in the center. Each nozzle had a 2.44 m radius of throw to provide 100% nozzle- to-nozzle overlap.

Irrigation system distribution uniformity (DU) and output in each treatment replicate was tested in 2009 using 16 rain gauges randomly interspersed throughout the production area and allowed to collect water for 20 min. The average application rate was 0.79 $mm \cdot min^{-1}$ with a distribution uniformity of 74.8%. Distribution uniformity and output in each treatment replicate was again tested in 2010. The average application rate was 0.77 $mm \cdot min^{-1}$ and the DU was 76.8%.

Plant Material

Rooted cuttings of *Aronia arbutifolia* Persh. 'Brilliantissima', *Cornus sericea* L. 'Farrow', *Hydrangea paniculata* Sieb. 'Limelight', *Itea virginica* L. 'Morton', *Physocarpus opulifolius* Maxim. 'Seward', *Spiraea media* F. Schmidt 'Darsnorm', *Thuja plicata* Donn.'Grovepli', and *Weigela florida* A. DC. 'Alexandra' were obtained from a commercial nursery in 5.7 x 5.7 cm plug containers on 1 August 2008. They were planted in 10.2 L containers with an 85 pine bark : 15 peat moss (vol:vol) substrate between 2 – 9 Sept. 2008 for use in the 2009 study. Plants were overwintered from 2008 to 2009 in a minimally-heated (-2.2^{o} C) quonset house covered with 4 mil overwintering film permitting 30% light transmission. In spring 2009, the film was removed and plants uniformly irrigated as needed until beginning the treatments. From the same nursery, cuttings of *Hydrangea arborescens* L. 'Abetwo', *Hydrangea paniculata* 'Limelight', *Rhus aromatica* Aiton 'Gro-Low', *Spiraea fritschiana* C.K. Schneid. 'Wilma', *Syringa meyeri* C.K. Schneid. 'Palibin', *Syringa* x*hyacinthiflora* Rehd. 'Evangeline', *Viburnum dentatum* L. 'Ralph Senior', and *Weigela florida* 'Alexandra' were potted as described above between 15 - 18 Sept. 2009 for use in the 2010 study. All cultural practices in both years except irrigation were identical for all treatments. On 9 June 2009 and 22 June 2010, 54 g of 19-2.6-10 (%N-P-K) controlled release fertilizer with micronutrients (Harrell's Inc., Lakeland, FL) was topdressed to each container. Total quantities of NO_3^--N and PO_4^{3-}-P applied in both 2009 and 2010 were equivalent to 285 $kg{\cdot}ha^{-1}$ and 39 $kg{\cdot}ha^{-1}$, assuming identical container spacing to this study and 100% land utilization. Predicted release duration at substrate temperatures of 21.1^{o} C and 26.7^{o} C ranged from 6 to 5 months. Weeds were removed by hand pulling as necessary.

Experimental Design

Four irrigation treatments were replicated three times and randomly assigned to 12 production areas in a completely randomized design. The treatments were: 1) control application of 19 $mm \cdot ha^{-1} \cdot d^{-1}$, 2) irrigation applied to replace 100% daily water use (100DWU), 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle (100-75), and 4) a 3-day application cycle replacing 100% DWU on the first day and 75% DWU on the second and third days (100-75-75). Each treatment replicate contained six subreplicates of each of the eight shrub species for a total of 96 experimental plants in each production treatment replicate. Experimental plants were randomized in six rows of eight at the center of the production area and inset at least 1.2 m from the edge with guard plants surrounding the perimeter to reduce edge effects. Guard plants consisted of several species having similar growth rates to the experimental plants and were arranged in the same sequence in each treatment replicate.

Daily Water Use and Irrigation Scheduling, 2009

Substrate volumetric water content (SVWC) was measured in 2009 for every plant using a time domain reflectometry (TDR) soil moisture sensor (ThetaProbe Type ML2x, Delta-T Devices Ltd., Cambridge, U.K.) and digital reader (ThetaMeter Hand-Held Readout Unit Type HH1, Delta-T Devices Ltd.). At initiation of the study, irrigation was applied until the substrate for all plants exceeded container capacity. Gravimetric water was allowed to drain for 30 min. Then an initial SVWC measurement was taken for each plant, and a final measurement was taken after 24 h. The Theta probe was inserted vertically into the substrate to a depth of 6 cm in three locations 120^{o} apart halfway between the center and the outer edge of the container. The measurements were converted to SVMC using a substrate-specific equation developed by Warsaw et al. (2009a) for the same substrate. The SVWC differential was multiplied by the average container substrate volume (9.7 $L \cdot container^{-1}$) to determine daily water use (DWU). Irrigation was then applied daily beginning at 0700 HR through a uniform overhead system to meet the needs of the lowest water user(s). Any taxa requiring more than 50 mL (0.89 mm) in addition to the base irrigation level received the balance by hand watering. Control and DWU-based irrigation run times were rounded up to the nearest whole min and programmed into a irrigation controller (Rain Bird ESP-12LX Plus, Rain Bird Corporation; Azusa, CA). Irrigation began at 0700 HR daily. New DWU were obtained approximately every 21 d, and irrigation was adjusted accordingly.

Daily Water Use and Irrigation Scheduling, 2010

In 2010, time capacitance soil moisture sensors (Model 10HS, Decagon Devices, Inc.; Pullman, WA) replaced the ThetaProbe to provide continuous real-time SVWC sampling and irrigation control. A total of 96 sensors, one per species in each replicate, were connected in single-ended configuration to an multiplexer (AM16/32B, Campbell Scientific, Inc.; Logan, UT), which was operated by a micrologger (CR3000, Campbell Scientific, Inc.). The micrologger recorded SVWC for each probe at 15 min intervals from 23 June to 31 October 2010. A relay controller (SDM-CD16AC, Campbell Scientific, Inc.) connected to the micrologger controlled the irrigation solenoid valves located at each treatment replicate. A common wire carrying 24 V alternating current power from the “Valve Test” terminal on the irrigation controller was connected to the relay controller for irrigation solenoid valve actuation.

On 20 June 2010, each of the 96 sensors was individually calibrated to the substrate *in situ*. Irrigation was applied to bring the substrate to container capacity, and each container was weighed after drainage ceased using a electric balance (PM 30, Mettler-Toledo, Inc.; Columbus, OH). Five subsequent weights were taken during a 2 d dry-down period and recorded with coinciding sensor output. These data were plotted using Microsoft Excel (2007) and the trend line feature was used to obtain a single best-fit quadratic equation. Calibrations were verified using the PROC REG function in SAS (SAS Institute; Cary NC) before inclusion in the irrigation control program.

Beginning on 23 June 2010 at 0700 HR, DWU was calculated in the first irrigation zone as (see Figure 1.1):

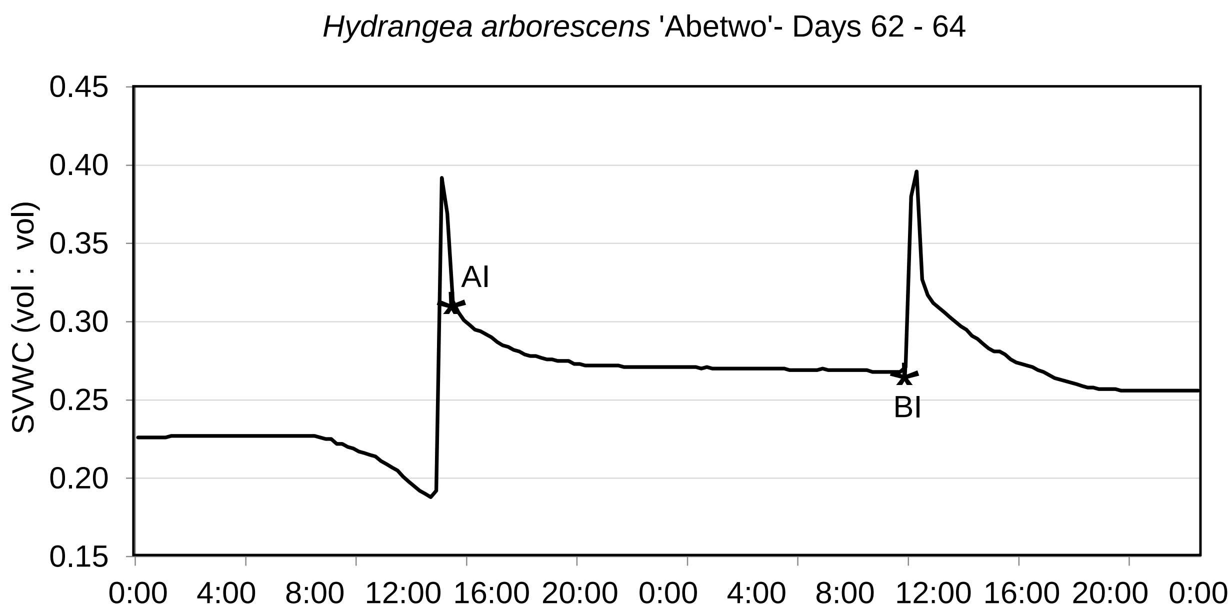
$$\text{DWU} = \text{AI} - \text{BI} * \text{substrate volume in container}$$

where AI is the SVWC value 1 h from the conclusion of the current irrigation event, BI is the SVWC value immediately preceding irrigation on the following day approximately 23 h later, and the substrate volume in the containers was 9690 ml. A run time was then calculated for each taxon in the irrigation zone by:

$$\text{Run Time} = \text{DWU} / 0.673$$

where 0.673 is the irrigation system application rate in $mL \cdot s \cdot container^{-1}$. The highest

Figure 1.1. Illustration of daily irrigation program operation on CR3000 logger (Campbell Scientific, Inc.; Logan, UT) using 15 min substrate volumetric water content (SVWC) scans for the calculation of daily water use (DWU). Example shown is for *Hydrangea arborescens* ‘Abetwo’ in the 100DWU treatment from 0000 HR on 23 August to 0000 HR 25 August 2010. Program operation corresponding to each letter described in text.



run time from the 8 plant taxa was selected, the treatment fraction applied (1.0 or 0.75, depending on treatment cycle), and irrigation initiated for the required duration. The micrologger repeated this process in all treatment replicates each day for the duration of the study. However, with no initial SVWC to reference from previous days, substrate moisture had to be raised to container capacity [(CC= 0.323 SVWC (vol : vol)] to obtain the first AI value on day 0 prior to the first calculation of DWU in the experiment.   From 0300 HR to 0600 HR on 22 Jun, 23.61 mm of steady rainfall occurred, which added 1.32 L to each container. This was considered sufficient to bring the substrate to container capacity for treatment commencement on 23 Jun.

Plant Performance

To standardize for environmental conditions between the two seasons, comparisons of water needs between the different species grown can be made using crop coefficients (K_C), which were determined using the formula $K_C = ET_A / ET_0$ (Allen et al., 1998). These calculations were made for each taxon in both years using data obtained from the on-site weather station (www.enviroweather.msu.edu). Plants were classified in this study as low ($K_C < 2$), moderate ($2 \leq K_C < 3$), or heavy ($K_C \geq 3$) water users as described by Warsaw et al. (2009a).

Monthly growth index (GI) was calculated to assess plant performance under the four irrigation treatments. Prior to the first measurement, all taxa were pruned to a uniform size. Then plant height (H) measurements were taken from the container rim. Plant widths were measured along the north – south (W_{NS}) and the east – west axis (W_{EW}) axis, and GI was calculated as $[(H + W_{NS} + W_{EW}) / 3]$. A permanently affixed container label was used to maintain orientation of the plants. For *Rhus aromatica* 'Gro-Low', *Viburnum dentatum* 'Ralph Senior', and *Weigela florida* 'Alexandra', plant shoot dry weight was measured at the end of the season in 2010 using three plants taken from each treatment replicate. The stem was cut at the substrate surface, and the entire top was bagged, oven dried, and weighed.

Using the PourThru leachate extraction procedure (Wright, 1986) electrical conductivity (EC) and pH were determined using an EC meter and a pH meter (Horiba Cardy Twin EC Meter; Horiba Cardy Twin pH Meter, Spectrum Technologies, Inc., Plainfield, IL). Testing was performed 30 to 60 min after irrigation for each taxa using the same test plant throughout the season.

Both mid- and late-season foliar samples were collected from five taxa in 2009 and six taxa in 2010. Sixty recently fully-expanded leaves were collected between the subreplicates of individual taxa within every treatment replicate. Samples were maintained in a cooler at $3^{o}C$ overnight then taken to the Michigan State University Soil and Plant Nutrient Laboratory (East Lansing, MI) the day after sampling. Percent (dry weight) N, P, K, Ca, Mg, Na, S, and concentration Fe, Zn, Mn, Cu, B, and Al were analyzed. The laboratory used the Dumas combustion procedure (AOAC 968.06; Horwitz, 2005) to determine foliar N. Minerals were dissolved from organic material using open vessel microwave digestion (SW846-3050B) with mineral analysis determined using inductively coupled argon plasma (ICAP analysis (AOAC 985.01; Horwitz, 2005).

Statistical analysis

Data for each species were analyzed individually for irrigation volume, DWU, K_C, GI, GII, dry weight, water use efficiency (WUE), dry weight water use efficiency (WUE_{dw}), substrate EC and pH, and foliar nutrient content. Data normality were checked using the PROC UNIVARIATE procedure in SAS (SAS Version 9.1; SAS Institute, Cary, NC). DWU data showed several outliers due to a variety of factors ranging from probes becoming dislodged in the substrate to rodent damage. Consequently, any DWU values in excess of 3000 ml were removed excluded from the analyses for DWU, K_C, and WUE. Data were tested with analysis of variance using the PROC GLM procedure of SAS. When significant ($\alpha = 0.05$), Tukey's Honestly Significant test was used to separate means. After the experiment was left unattended for 4 d when air temperatures and ET_0 averaged 31.4°C and 4.56 mm, irreversible wilt and leaf scorch was discovered on *H. paniculata* 'Limelight' on 31 August 2010 (day 70) in the last 100-75-75 treatment replicate to run each day. The fault occurred because the farm irrigation well pump was not scheduled to run long enough during this high period of ET_0. Therefore, data from that treatment replicate was excluded from analysis of WUE throughout the entire season and DWU, K_C, GI, EC, pH, and foliar nutrient concentration excluded from day 70 onward.

Results and Discussion

Irrigation Volume, Daily Water Use, and Plant Growth

Cumulative and average daily ET_0 for the 2009 treatment period equaled 414 mm and 3.23 mm and in 2010 were 431 mm and 3.29 mm. A total of 310 mm and 233 mm of rainfall (Figure 1.2) occurred during the 2009 and 2010 treatment periods. In 2009, irrigation was not applied on three days when rainfall events exceeded 19 mm. During the treatment period, total irrigation applied to the control was 2483 mm (134.1 $L \cdot container^{-1}$; Table 1) in 2009 and 2594 mm (140.1 $L \cdot container^{-1}$) in 2010.

Figure 1.2. Daily (bars) and cumulative (line) precipitation from 11 June to 14 October (Day 126) 2009 and 23 June to 31 October 2010 (Day 131). Data obtained from the Enviro-weather Automated Weather Station Network.

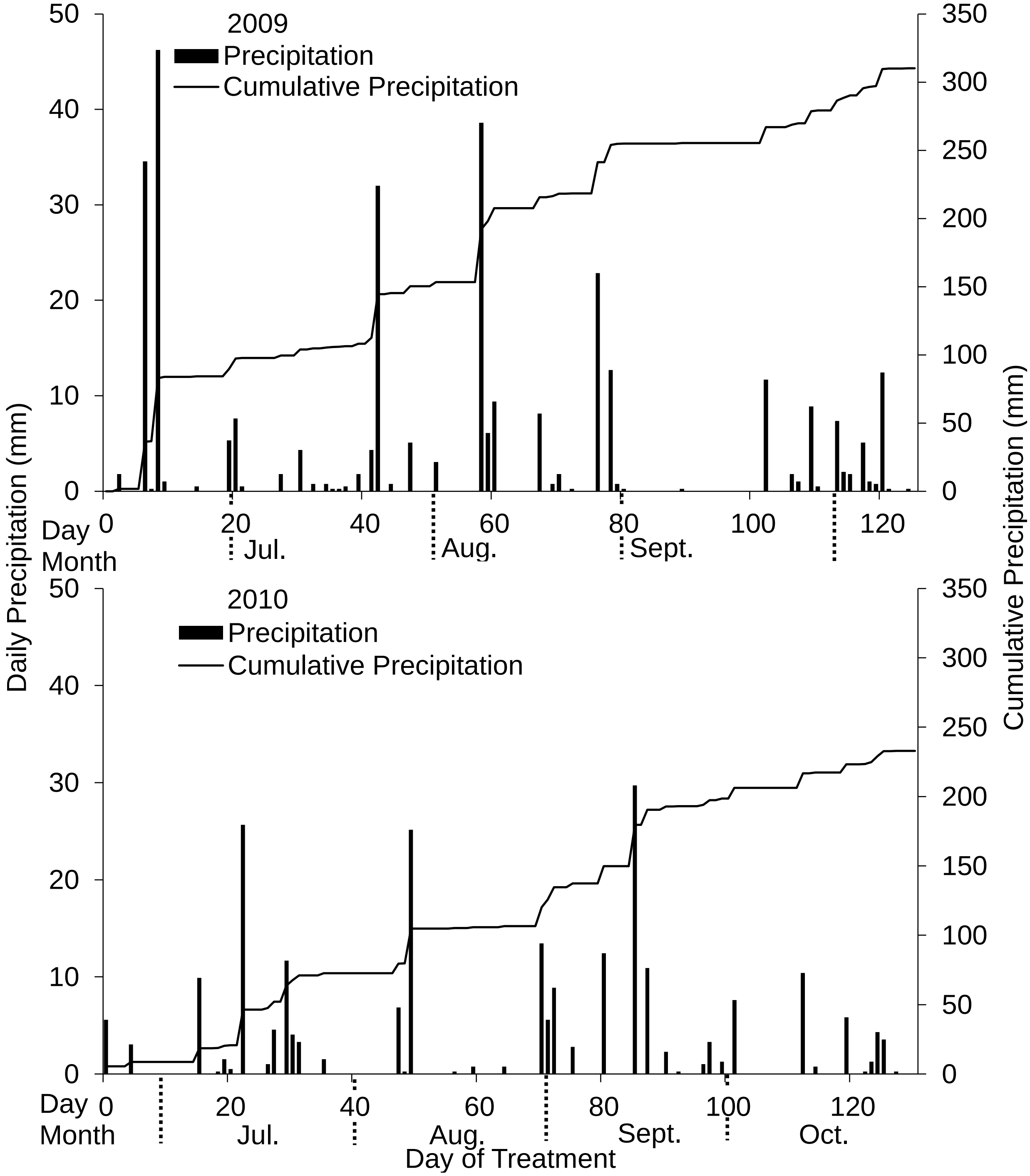
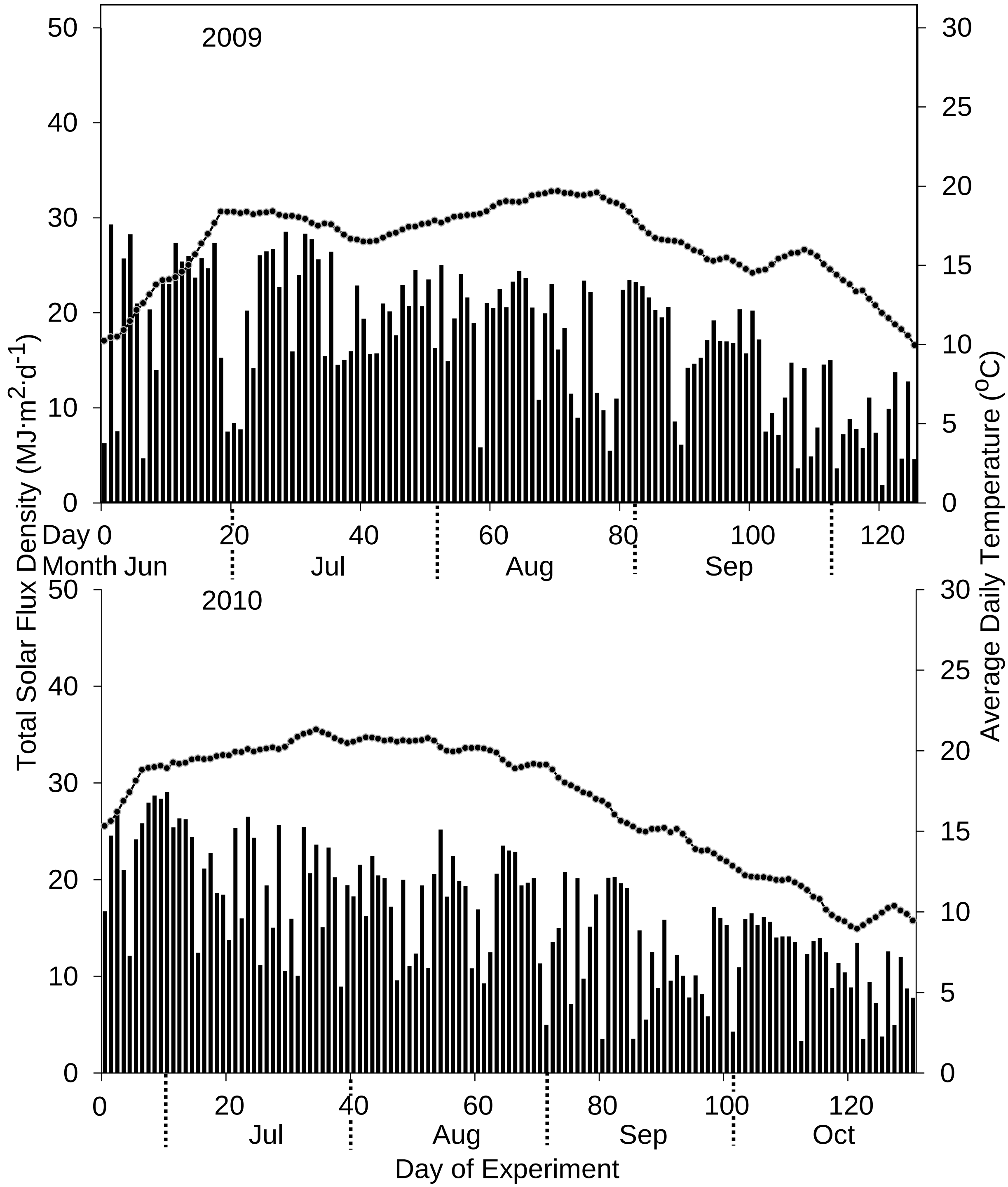


Figure 1.3. Daily total solar flux density (bars) and daily average temperature (line) from 11 June to 14 October (Day 126) 2009 and 23 June to 31 October 2010 (Day 131). Data obtained from the Enviro-weather Automated Weather Station Network.



In 2009, *I. virginica* 'Morton' only received the base irrigation rate, never any hand watering. All other taxa required hand water applications for at least one interval between DWU measurements (Table 1.1). Water reductions compared to the control for *H. paniculata* 'Limelight' were 7%, 19%, and 23% in the 100DWU, 100-75, and 100-75-75 treatments, respectively. Water applications were reduced 48%, 55%, and 57% for *I. virginica* 'Morton' in the 100DWU, 100-75, and 100-75-75 treatments, respectively. Table 1.1 does not report average water application to each taxon grown in 2010 because all taxa within each treatment replicate received uniform irrigation applications based on the highest water use plant each day. Compared to the control, total irrigation applications in 2010 were 19% and 50% greater in the 100DWU and 100-75 treatments while the 100-75-75 treatment received 18% less water.

Average DWU was highest in 2009 for *H. paniculata* 'Limelight' in the 100DWU treatment at 17.3 $mm \cdot day^{-1}$ and lowest for *A. arbutifolia* 'Brilliantissima' and *T. plicata* 'Grovepli' in the 100DWU treatment at 8.8 and 9.0 $mm \cdot container \cdot day^{-1}$ (Table 1.2). Water use of both *C. sericea* 'Farrow' and *I. virginica* 'Morton' was lower in the 100DWU treatment than the control, but did not differ for the deficit treatments. No other differences existed between treatments for individual taxa. Compared to 2009 in which DWU was measured intermittently, more differences were observed when DWU was calculated daily in 2010. Highest DWU was observed in *H. paniculata* 'Limelight' than any other species, except in the control and 100-75 treatment in which it did not differ from *H. arborescens* 'Abetwo'. *Rhus aromatica* 'Gro-low' and *H. arborescens* 'Abetwo' had similar DWU in the control and 100-75-75 treatments. All three of these high water-use taxa exceeded 75 cm at the end of the season, which is also larger than the other

Table 1.1. Total irrigation application (L·container^{-1}) to 4 irrigation treatments from 11 June (Day 1) to 14 October 2009 (Day 126) and 23 June (Day 1) to 31 October 2010 (Day 131).

Taxa	Control^{z}	100DWU	100-75	100-75-75
2009				
Aronia arbutifolia 'Brilliantissima'	134.1	78.2	68.6	65.4
Cornus sericea 'Farrow'	134.1	100.5	88.3	84.3
Hydrangea paniculata 'Limelight'	134.1	124.7	108.8	103.3
Itea virginica 'Morton'	134.1	69.1	60.5	57.6
Physocarpus opulifolius 'Seward'	134.1	100.7	88.1	84.1
Spiraea media 'Darsnorm'	134.1	78.8	69.3	66.1
Thuja plicata 'Grovepli'	134.1	76.9	67.3	64.1
Weigela florida 'Alexandra'	134.1	113.5	99.3	94.8
2010				
Average water application (mm·d^{-1}) to all taxa	140.1 C^{y}	167.3 B	209.8 A	115 D

^{z}Control = 19 mm·application^{-1} (1.07 L·container^{-1}·day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on 2009) lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day as necessary; 2010) highest DWU of the 8 taxa in each treatment replicate each day.

^{y}Means separation performed with Tukey's Test (α = 0.05), n = 3.

taxa in the study. The two *Hydrangea* taxa exhibited higher DWU in the 100-75 treatment than either the 100DWU treatment or the 100-75-75 treatment, both of which received less water than the 100-75 treatment. Lowest water use taxa included

Table 1.2. Season average daily irrigation application ($mm \cdot container^{-1} \cdot d^{-1}$) and average daily water use ($mm \cdot container^{-1} \cdot d^{-1}$) of eight shrubs grown in 10.2 L containers under four irrigation treatments administered 11 June (Day 1) to 14 October 2009 (Day 126) and 23 June (Day 1) to 31 October 2010 (Day 131).

2009	Control[z]	100DWU	100-75	100-75-75
Average base water application ($mm \cdot d^{-1}$)	19.0 A	9.8 B	8.6 C	8.2 C
Taxa				
Aronia arbutifolia 'Brilliantissima'	10.7 Aa	8.8 Ac	9.4 Ac	10.5 Ac
Cornus sericea 'Farrow'	14.9 Aa	10.0 Bbc	13.2 ABab	13.4 ABbc
Hydrangea paniculata 'Limelight'	14.0 Aa	17.3 Aa	15.9 Aa	17.1 Aa
Itea virginica 'Morton'	12.9 Ba	9.6 Bbc	10.6 ABbc	10.6 ABc
Physocarpus opulifolius 'Seward'	13.1 Aa	13.2 Ab	13.0 Aab	14.6 Aab
Spiraea media 'Darsnorm'	10.7 Aa	9.7 Abc	12.4 Abc	11.5 Abc
Thuja plicata 'Grovepli'	11.0 Aa	9.0 Ac	9.0 Ac	11.7 Abc
Weigela florida 'Alexandra'	14.9 Aa	11.9 Abc	13.5 Cab	13.9 Aabc
2010				
Average water application ($mm \cdot d^{-1}$)	19.1 C	22.8 B	28.6 A	15.4 D
Taxa				
Hydrangea arborescens 'Abetwo'	15.0 Bab	9.4 Ccd	20.9 Aa	6.4 Cc
Hydrangea paniculata 'Limelight'	18.4 Ba	18.5 Ba	22.5 Aa	15.1 Ba
Rhus aromatica 'Gro-Low'	13.0 Abc	12.8 Ab	14.0 Ab	6.9 Bbc
Spiraea fritschiana 'Wilma'	8.5 Bc	11.1 Abc	8.6 Bc	5.6 Cc
Syringa meyeri 'Palibin'	3.7 Be	10.0 Abc	9.0 Ac	4.8 Bc

Table 1.2 (cont'd)

2010	Control[z]	100DWU	100-75	100-75-75
Syringa x*hyacinthiflora* 'Evangeline'	10.8 Acd	2.3 Cf	3.5 BCd	4.6 Bc
Viburnum dentatum 'Ralph Senior'	4.3 Bd	7.0 Ade	4.2 Bd	6.5 Ac
Weigela florida 'Alexandra'	10.8 Ac	5.1 Bef	5.7 Bcd	10.1 Ab

[z]Control = 19 mm·application^{-1} (1.02 L·day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on 2009) lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day in DWU treatments as necessary; 2010) highest DWU of the 8 taxa in each treatment replicate each day.

[y]Separation of means performed with Tukey's Test (α = 0.05). Average daily irrigation application: 2009) n = 126, 2010) n = 393. Average DWU: 2009) n= 108, 2010) n= 393. Means followed by the same letters within rows are not different.

[x]Comparisons between means in each column are marked with lowercase letters. Means of the same letters are not different; Tukey's Test (α = 0.05), 2009: n = 108, 2010: n=393.

S. meyeri 'Palibin' at 3.7 mm in the control, *S.* x*hyacinthiflora* 'Evangeline' at 2.3 mm and 4.6 mm in the 100DWU and 100-75-75 treatments, and *V. dentatum* 'Ralph Senior' at 4.2 mm in the 100-75 DWU treatment. Additionally, *R. aromatica* 'Gro-low' and *S. fritschiana* 'Wilma' showed lowest DWU in the 100-75-75 treatment.

Figures 1.4 and 1.5 show that DWU tends to steadily increase from June to mid-August with plant growth, hold steady in late summer as growth plateaus, decline in September, and again plateau late September through October. In 2009 (Fig. 1.5), DWU peaked on day 57 for all taxa when DWU also exceeded the control rate of

Figure 1.4. Plant Growth Index (GI), Daily Crop Coefficient (K_C), and Daily Water Use (DWU) from 10 June (Day 0) to 14 October 2009 (Day 126) for A) *Aronia arbutifolia* 'Brilliantissima', B) *Cornus sericea* 'Farrow', C) *Hydrangea paniculata* 'Limelight', D) *Itea virginica* 'Morton', E) *Physocarpus opulifolius* 'Seward', F) *Spiraea media* 'Darsnorm', G) *Thuja plicata* 'Grovepli', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers.

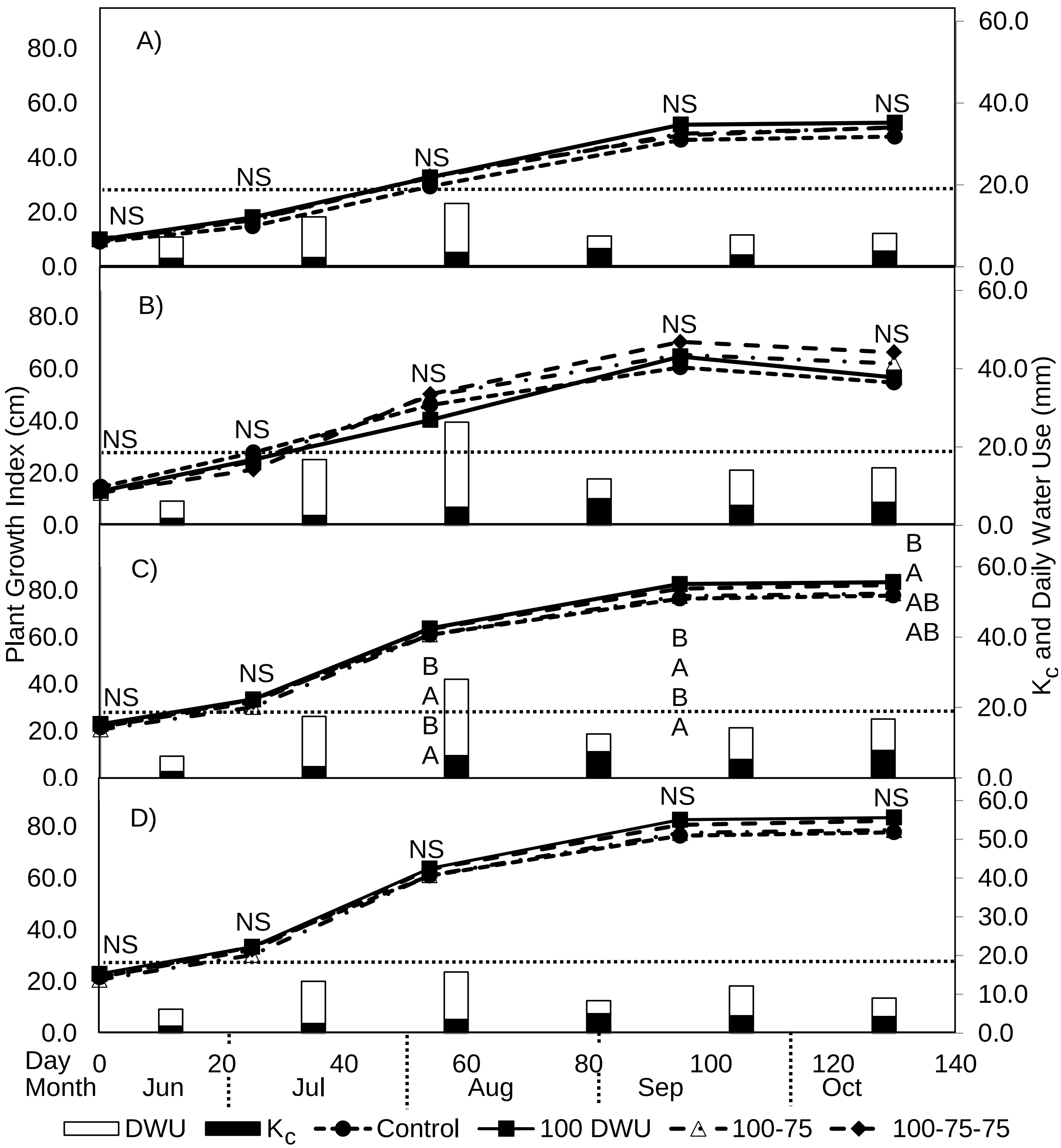
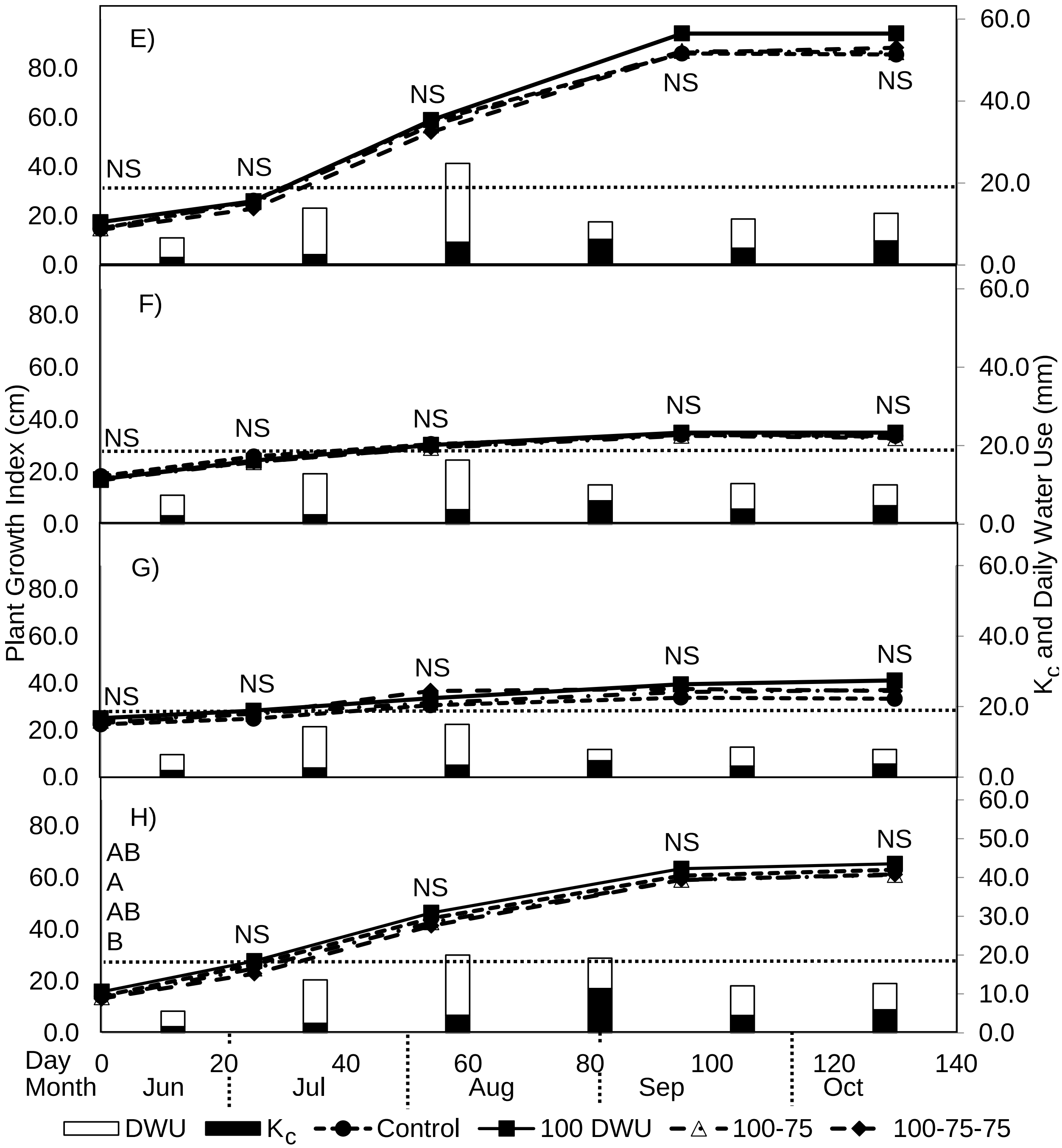


Figure 1.4 (cont'd)



Left y-axis indicates PGI (lines). Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant. n=18. Right y-axis indicates DWU where the entire bars represent DWU (mm)

Figure 1.4 (cont'd)
averaged from all treatments (n=72); shaded portions of bars represent daily K_C (DWU : ET_0, n=72). Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period; remaining water requirement supplied by hand each day as necessary. Dotted horizontal line indicates control treatment of $19mm \cdot application^{-1}$. Daily ET_0 values for calculation of K_C obtained from the Enviro-weather Automated Weather Station Network.

$19\ mm \cdot container^{-1}$ for *C. sericea* 'Farrow' (20.4 mm), *H. paniculata* 'Limelight' (28 mm), *P. opulifolius* 'Seward' (24.8 mm), and *W. florida* 'Alexandra' (20 mm). No other taxa peaked above the control on any other sampling day except *W. florida* 'Alexandra' on day 75 (DWU = 19.2mm). In 2010, DWU peaked on Day 55 (ET_0=4.92 mm) for *H. arborescens* 'Abetwo' (36 mm), *H. paniculata* 'Limelight' (43 mm), *R. aromatica* 'Gro-low' (32 mm), and *W. florida* 'Alexandra' (23 mm). For *Hydrangea arborescens* 'Abetwo', *H. paniculata* 'Limelight', and *R. aromatica* 'Gro-low', DWU peaked above the control irrigation rate for 19, 52, and 27 days, respectively. In contrast, many days preceding or following peak days had DWU far below the control. Thus, the data reveal that when intermittent sampling techniques are employed, under- or overestimation of DWU could result in applying too little or too much water between irrigation rate adjustments. Additionally, in October when temperatures and insolation fell to their lowest for the study (Figure 1.3), DWU did not peak above the control application rate for any taxa except *H. paniculata* 'Limelight', so the control rate was excessive in the majority of cases for the month.

Since DWU was based on the highest water user each day in 2010, lower- use taxa such as both *Syringa* species and *V. dentatum* 'Ralph Senior' were over-irrigated to varying degrees. In addition, these taxa never required more water than the control

Figure 1.5. Plant Growth Index (GI), Daily Crop Coefficient (K_C), and Daily Water Use (DWU) from 23 June (Day 1) to 31 October 2010 (Day 131) for A) *Hydrangea arborescens* ‘Abetwo’, B) *Hydrangea paniculata* ‘Limelight’, C) *Rhus aromatica* ‘Gro-Low’, D) *Spiraea fritschiana* ‘Wilma’, E) *Syringa meyeri* ‘Palibin’, F) *Syringa* x*hyacinthiflora* ‘Evangeline’, G) *Viburnum dentatum* ‘Ralph Senior’, and H) *Weigela florida* ‘Alexandra’ grown in 10.2 L containers.

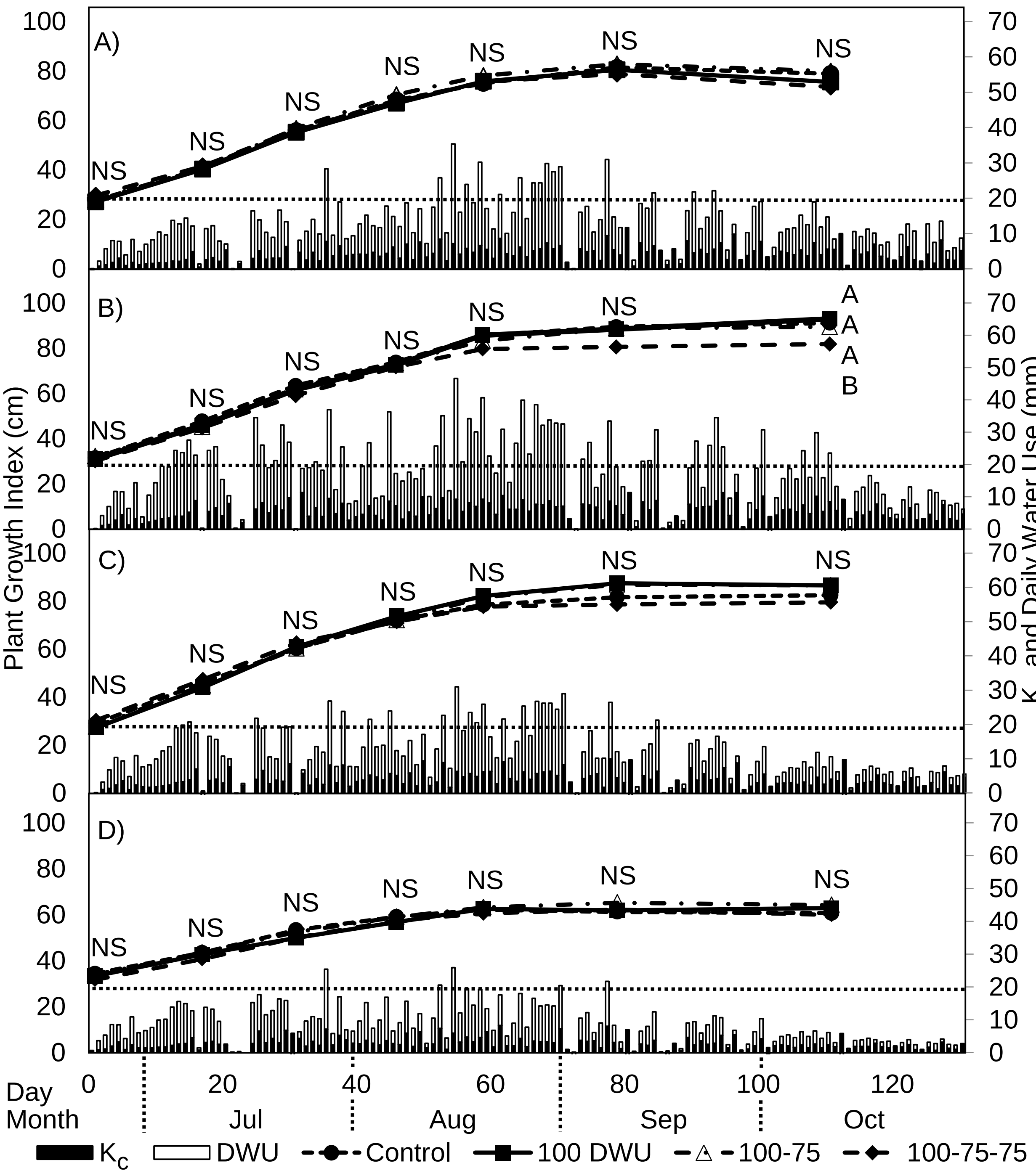
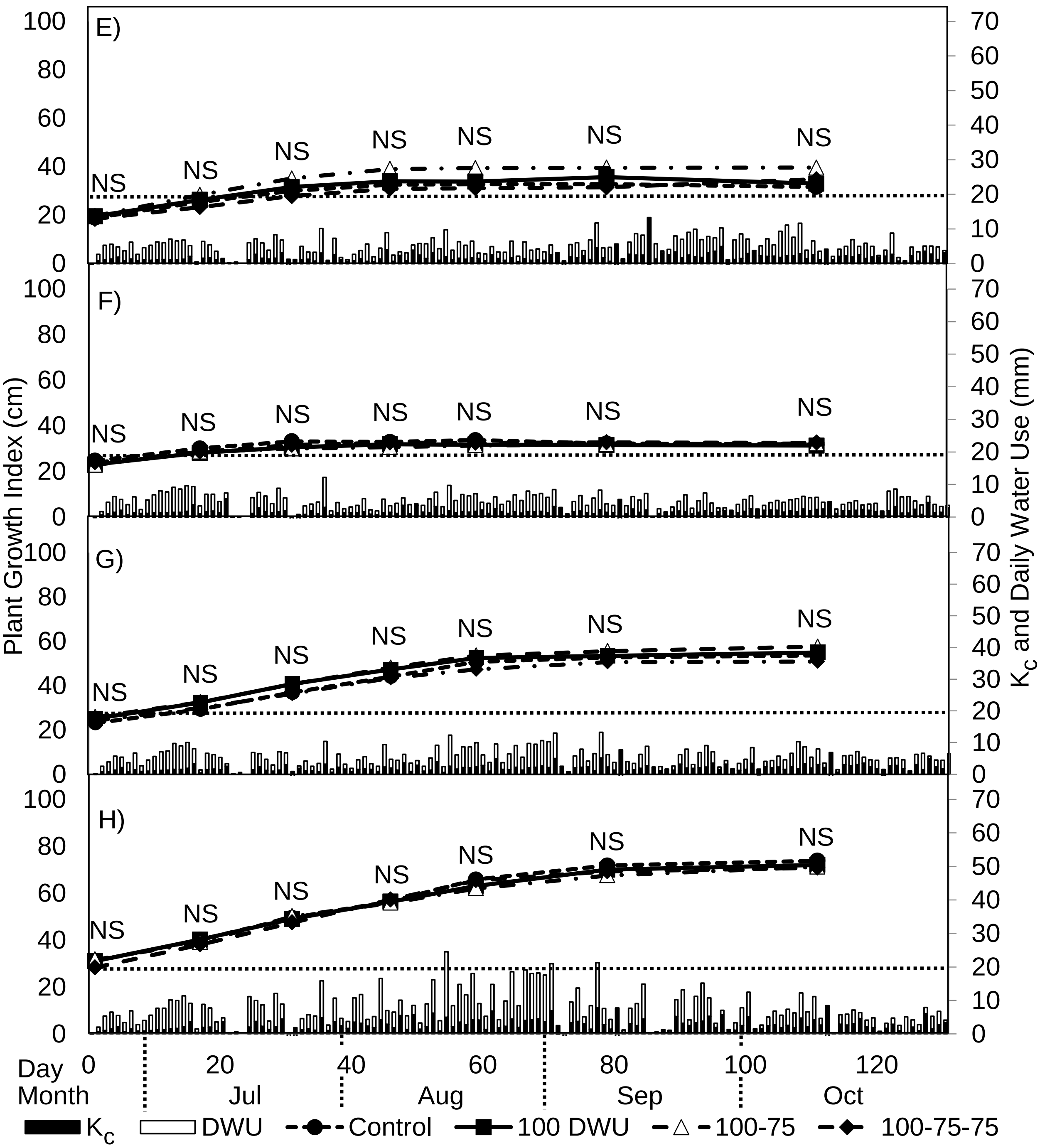


Figure 1.5 (cont'd)



Left y-axis indicates PGI (lines). Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant.

Figure 1.5 (cont'd)
n=18. Right y-axis indicates DWU where the entire bars represent DWU (mm) averaged from all treatments (n=12); shaded portions of bars represent daily Kc (DWU : ET0, n=12). Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day. Dotted horizontal line indicates control treatment of 19mm.application-1. Daily ET0 values for calculation of Kc obtained from the Enviro-weather Automated Weather Station Network.

throughout the season. Had irrigation been individually applied to all taxa based on their respective DWU, water savings could have been 88%, 92%, and 89% for *S. xhyacinthiflora* 'Evangeline' in the 100DWU, 100-75, and 100-75-75 treatments (considering both fraction and day cycle), respectively. A moderate water use species such as *S. media* 'Wilma' could have saved 73%, 79%, and 55% in its respective 100DWU, 100-75, and 100-75-75 treatments where in the same treatments an even heavier user such as *R. aromatica* 'Gro-low' could save 33%, 30%, and 74.5%, respectively. Conversely, *H. paniculata* 'Limelight' would have received 3.2% more water in the 100-75 treatment than the control. Thus, in addition to saving water for low and moderate-use taxa, irrigation scheduling based on DWU accommodates the demands of high water users to ensure they are not under-watered.

In both 2009 and 2010, plant GI steadily increased in June and July, tapered between August and September, and reached a plateau in September to October. In 2009, *H. paniculata* 'Limelight' control plants were smaller than the 100DWU and 100-75-75 treatment plants on days 46 and 79. From day 52 to 74, plants in the 100DWU and 100-75-75 treatments received 34.5 L and 28.8 L compared to the control, which received 23.5 L. At the conclusion of the study, GI for *H. paniculata* 'Limelight' was still lower in the control than 100DWU treatment even though more water was applied to the control over the season at 134.1 L versus the 100DWU at 124.7 L (Table 1.1). This higher growth in the 100DWU treatment may have resulted from better timing of water application volumes during the plant's growth or physiological development compared to the steady control rate. When DWU scheduling was conducted in real time, no growth differences were observed on any measurement days throughout 2010 except the final day. On day 108, *H. paniculata* 'Limelight', the largest-growing taxa overall, showed reduced growth in the 100-75-75 treatment compared to other DWU treatments or the control. Under production conditions, all plants would have been considered marketable. Contrasting the two scheduling methods used in 2009 and 2010, intermittent DWU quantification risks over- or under-estimation of crop water needs for the interval between measurements whereas real-time estimation compensates for changes in DWU at daily resolution. Still, substantial water reductions were realized using intermittent measurements without reductions in growth in this study or by Warsaw et al. (2009a). Others have demonstrated substantial reductions in water applications when irrigating based on ET_A without sacrificing growth. Growing in 2.4 L containers, *Viburnum odoratissimum* grew to the same size using 39% less water when irrigated based on ET_A-based compared to a fixed irrigation rate of 1 $cm \cdot d^{-1}$ (Million et al., 2010). In *Ligustrum japonica* growing in 11.4 L containers, 1690 mm of irrigation was applied based on ET_A and produced marketable plants 3 weeks faster than a manual total application volume of 2100 mm (Beeson and Brooks, 2008). Real-time irrigation scheduling using DWU shortened the production of *Gardenia jasminoides* by as much 64% at one production nursery in Georgia by increasing its rate of growth

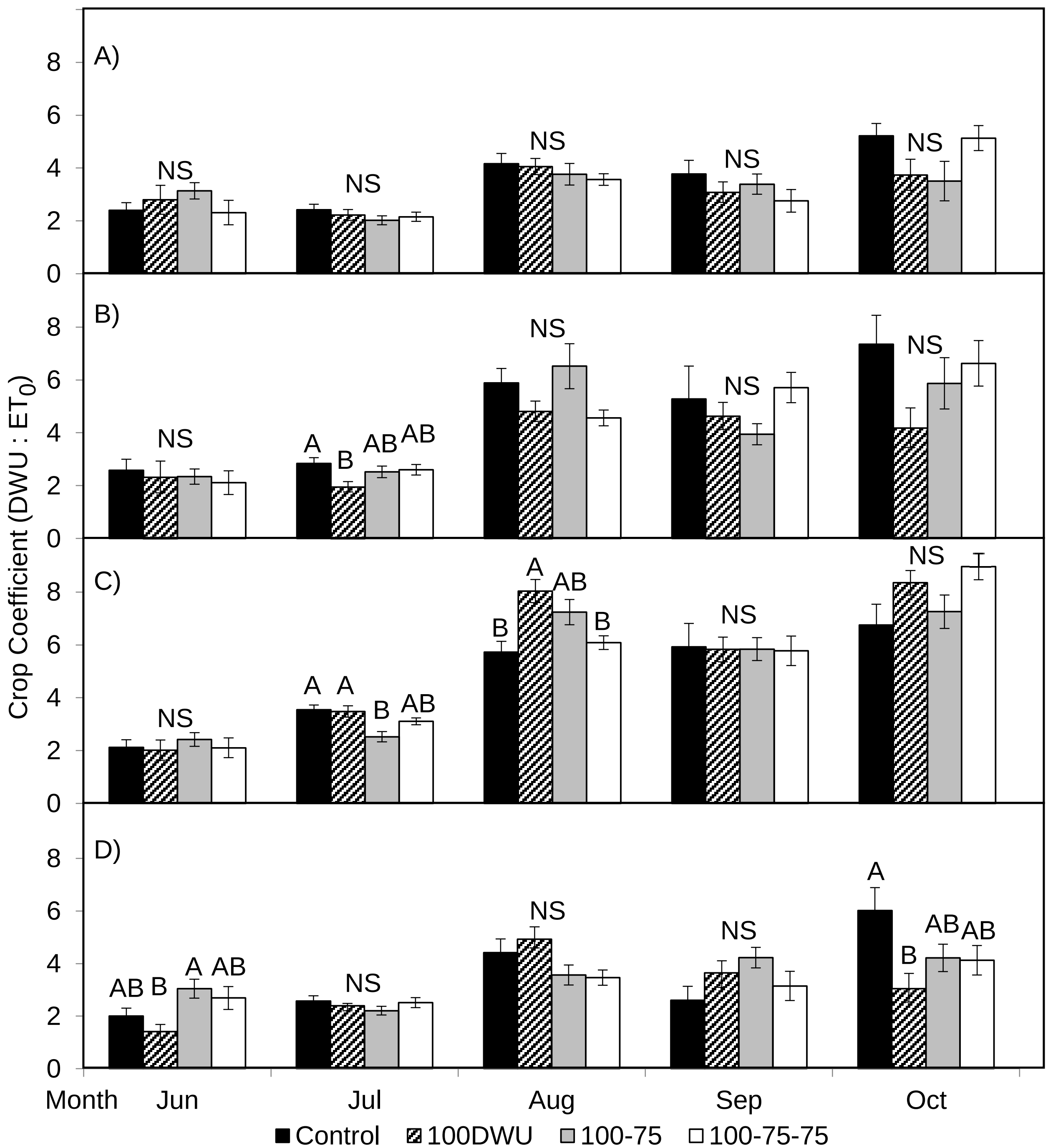
(Chappell et al., 2013). Other incentives for sensor adoption include shortened crop production windows that free up space for new crops sooner, reduced losses from disease, and increased overall crop profitability (Lichtenberg et al., 2013).

In a study of 24 ornamental shrub taxa, Warsaw et al. (2009a) showed only one taxon in a deficit DWU treatment that grew less than the plants receiving 100% of their DWU. Their findings and those from the current study strongly suggest that a buffer exists in many ornamental plant species against light to moderate moisture deficits before growth reductions occur. Although tension curves were not developed for the 85 pine bark : 15 peat moss (vol : vol) substrate used in this study, SVWC typically ranged from 0.32 (vol : vol) at CC to a minimum of around 0.15 before irrigation occurred. Since only *H. paniculata* 'Limelight' showed a reduction in growth in the greatest deficit (100-75-75) treatment, this would indicate that substrate moisture usually remained within the range of easily available water (EAW) (Lea-Cox, et al., 2011), while perhaps falling into the water buffering range on occasion.

Crop coefficients

For all taxa in 2009, DWU and K_C peaked mid-summer on 6 Aug. (ET_0=4.27 mm) and 28 Aug. (ET_0=1.03 mm) (Figure 1.4, shaded portion of bars). Season average K_C in 2009 ranged from 3.2 and 3.6 for *T. plicata* 'Grovepli' and *I. virginica* 'Morton' to 5.0 and 5.3 for *W. florida* 'Alexandra' and *H. paniculata* 'Limelight'. Under the classification system used by Warsaw et al. (2009a), all taxa were high water users in

Figure 1.6. Monthly Crop Coefficient (K$_C$) from 11 June (Day 1) to 14 October 2009 (Day 126) for A) *Aronia arbutifolia* 'Brilliantissima', B) *Cornus sericea* 'Farrow', C) *Hydrangea paniculata* 'Limelight', D) *Itea virginica* 'Morton', E) *Physocarpus opulifolius* 'Seward', F) *Spiraea media* 'Darsnorm', G) *Thuja plicata* 'Grovepli', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers.



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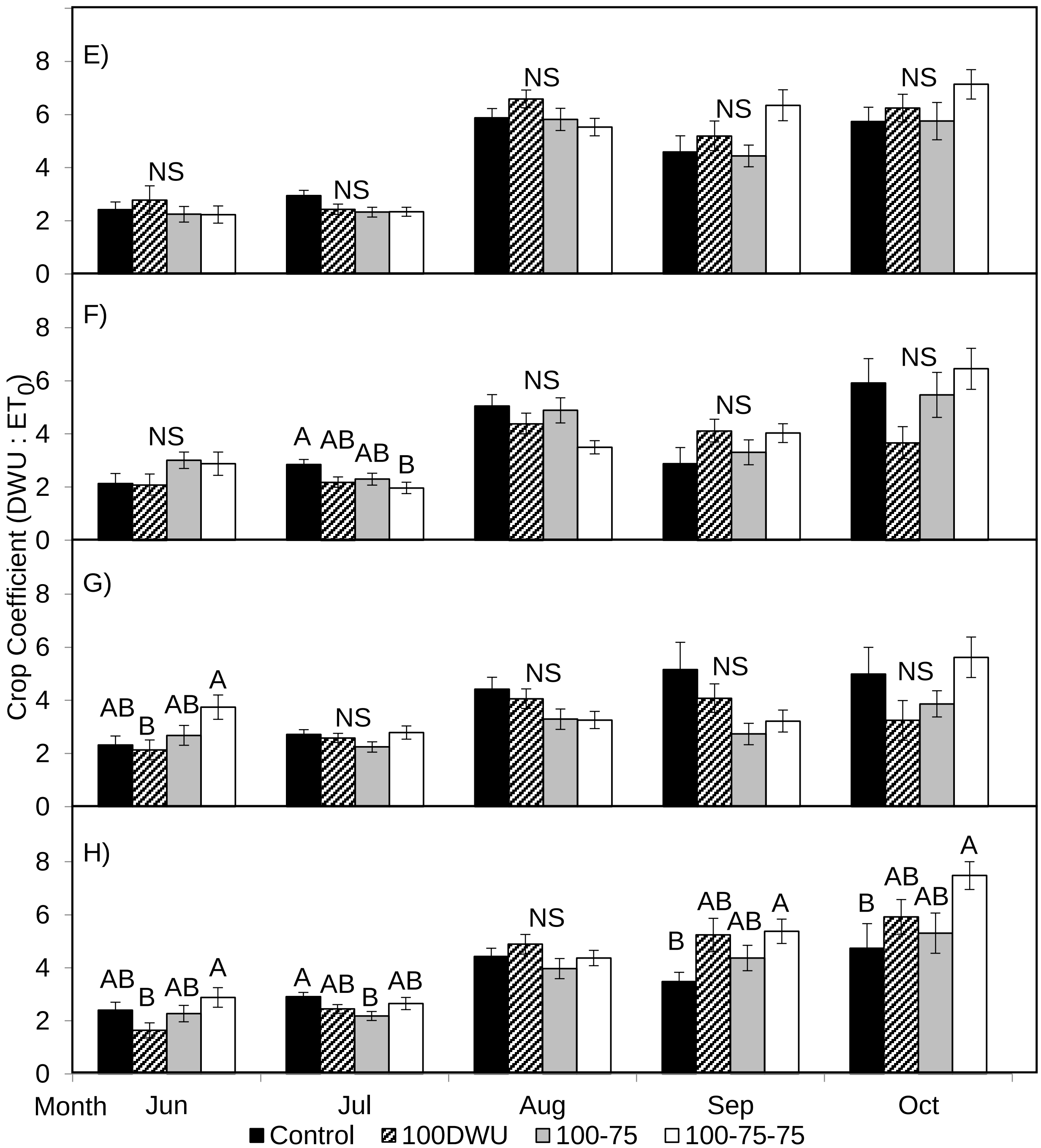


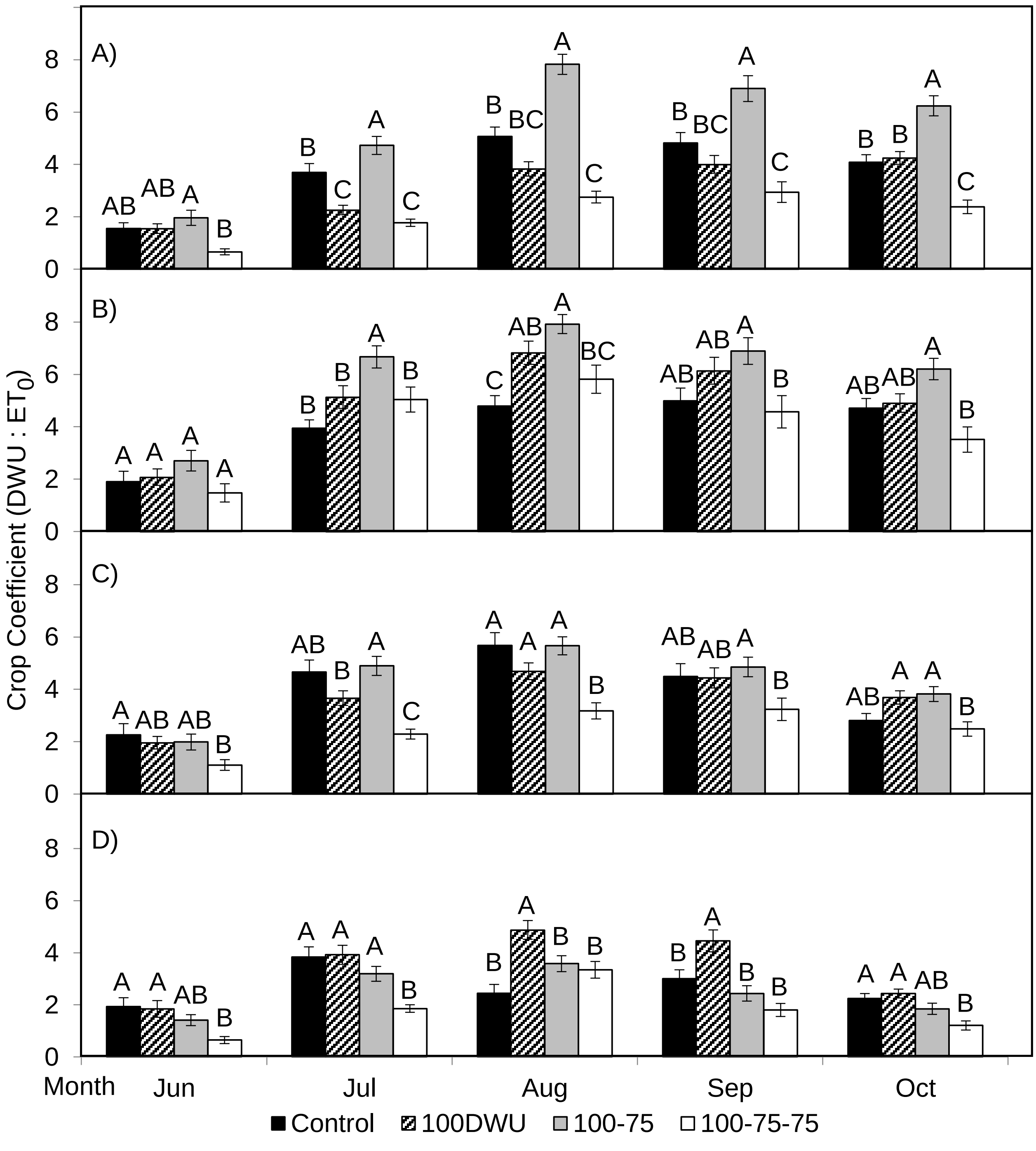
Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each month was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant. Jun, Jul, Sep, and Oct: n=18, Aug: n=36. Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period; remaining water requirement supplied by hand

Figure 1.6 (cont'd)
each day as necessary. Daily ET_0 values for calculation of K_C obtained from the Enviro-weather Automated Weather Station Network.

2009 (K_C >3.0). Similarly, in 2010, DWU peaked mid-summer on 16 Aug. (ET_0=4.92 mm), while highest K_C of 11.3 was observed on 11 Sep. (ET_0= 0.71 mm) for both *H. arborescens* 'Abetwo' and *H. paniculata* 'Limelight'. Highest K_C was also recorded on 8 Sep. for *R. aromatica* 'Gro-Low' at 9.9 (ET_0=2.0 mm) (Figure 1.5). These three taxa were all high water users in 2010 with season average K_C of 4.3, 5.4, and 4.1, respectively. *Spiraea fritschiana* 'Wilma', *V. dentatum* 'Ralph Senior', and *W. florida* 'Alexandra' were moderate users with K_C values of 2.8, 2.0, and 2.6, respectively. Low water users included *S.* x*hyacinthiflora* 'Evangeline' and *S. meyeri* 'Palibin' with average K_C of 1.8 and 1.9.

Because K_C values normalize for environmental variables (Allen et al., 1998), cross-season comparisons can be for the identical taxa. *Hydrangea paniculata* 'Limelight' was a high user in both 2009 and 2010 whereas *W. florida* 'Alexandra' was classified as a high water user in 2009, but only a moderate user in 2010. Using the same production site as the current study, Warsaw et al. (2009a) rated *C. sericea* 'Farrow' a high user at K_C of 3.4 in 2006 whereas it was rated K_C of 4.4 in 2009 by the current study (cumulative ET_0= 393.7 mm in 2006 VS 413.7 in 2009). In 2007, Warsaw et al., (2009a) rated both *S. fritschiana* 'Wilma' and *W. florida* 'Alexandra' high users at

Figure 1.7. Monthly Crop Coefficient (K_C) from 23 June (Day 1) to 31 October 2010 (Day 131) for A) *Hydrangea arborescens* 'Abetwo', B) *Hydrangea paniculata* 'Limelight', C) *Rhus aromatica* 'Gro-Low', D) *Spiraea fritschiana* 'Wilma', E) *Syringa meyeri* 'Palibin', F) *Syringa* x*hyacinthiflora* 'Evangeline', G) *Viburnum dentatum* 'Ralph Senior', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers.



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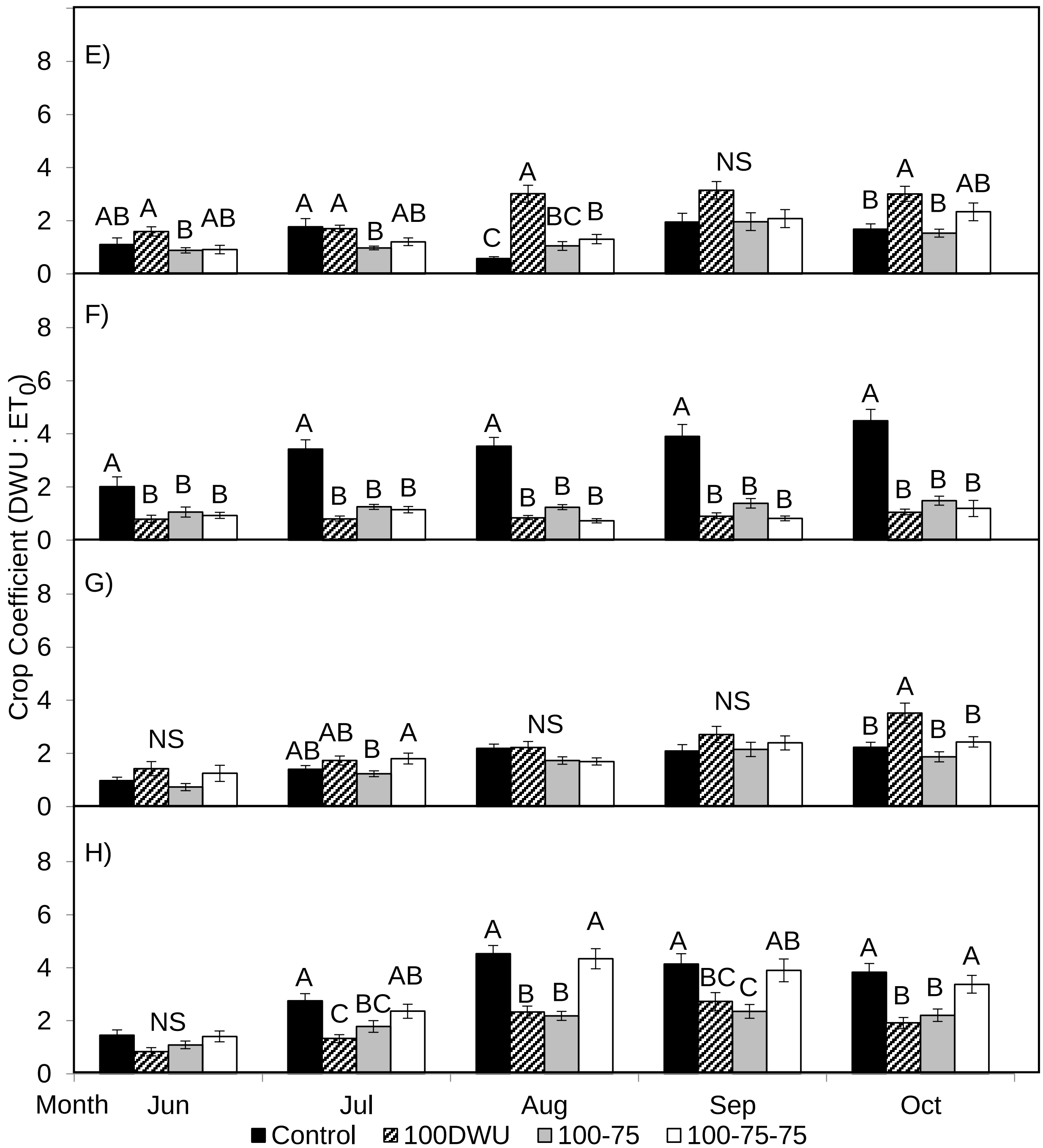


Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each month was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant. Jun: n=24 (except 100-75-75 treatment, n=16). Jul, Aug, and Oct: n= 93 (except 100-75-75, n= 62). Sep: n= 90 (except 100-75-75, n=60). Overhead irrigation scheduling based on highest

Figure 1.7 (cont'd)
DWU of the 8 taxa in each treatment replicate each day. Daily ET_0 values for calculation of K_C obtained from the Enviro-weather Automated Weather Station Network.

K_C =3.6 while these two taxa were rated moderate users at K_C = 2.8 and 2.6 in the current study during 2010 (cumulative ET_0= 490.1 mm in 2007 VS 430.8 in 2010). The values reported by Warsaw et al. (2009a) for identical taxa are likely higher than those reported in this study because cumulative ET_0 was higher in 2007 than 2010. Therefore, when making comparisons of K_C, the effect of both season duration and cumulative ET_0 should also be considered.

Irrigation treatments had an effect on K_C. When both irrigation applications and GI were higher in the 100DWU treatment than the control, *H. paniculata* 'Limelight', the plant with highest 2009 season average K_C, exhibited higher K_C in the 100DWU than control and 100-75 treatments in August. In July through October 2010, the high water use taxa, *H. arborescens* 'Abetwo', *H. paniculata* 'Limelight', and *R. aromatica* 'Gro-Low' had highest K_C in the 100-75 treatment (Figure 1.8), which also had the highest total water applications (Table 1.1). In contrast, low and moderate use species tended to show lowest K_C at higher irrigation rates. In June 2009, the lowest water users of the season, *I. virginica* 'Morton' and *T. plicata* 'Grovepli', each had lower K_C in the 100DWU than at least one other deficit treatment. In August 2010, the 100-75 treatment, which received the most water, had K_C values of 1.0, 1.2, and 1.7 for *S. meyeri* Palibin', *S.*

x*hyacinthiflora* ‘Evangeline’, and *V. dentatum* ‘Ralph Senior’. Because irrigation applications were based on the highest user in each treatment replicate in 2010, these taxa were over-watered most days throughout 2010, particularly mid-season when K_C peaked for high users.

In annual field crops, K_C begins increasing early in the season as leaf area index increases (USDA, 1993). Water use continues to increase through the rapid growth stage followed by a water use ceiling at full canopy cover. Late in the season, water use decreases in annual crops as they near harvest. During the current study, K_C began low and increased until plants reached their growth plateaus in mid-summer (Figures 1.7 and 1.8). At this point, K_C remained fairly stable for the rest of the season. Others have shown similar responses in ornamental shrubs with low K_C increasing as plants grow and develop, then stabilizing for the rest of the season (Niu et al., 2006).

Calendar month serves as a convenient interval to reevaluate K_C for seasonal changes in plant growth or environmental conditions (Schuch and Burger, 1997). In both 2009 and 2010, most taxa tended to show lowest K_C in June or July (Tables A-1 and A-2) when GI was also low (Figures 1.4 and 1.5). Crop coefficients of high water use plants varied by as much as 3.7 between months and were often highest as plants neared maximum seasonal growth in August to October. However, while K_C of high water users tended to increase between June and August, K_C was more static in low water use taxa. Similarly, Schuch and Burger (1997) found that K_C’s of low water use ornamental shrubs grown in containers are relatively consistent across warm and cool phases of a production cycle and thus serve as effective estimators of actual plant water use. While DWU fell in all plants from late August to October, K_C remained high during these times. Schuch and Burger (1997) showed a similar relationship between water use and K_C. The current study reveals that higher water use plants exhibit greater increases in K_C during active growth midseason than do lower water users, which remain relatively constant. Therefore, greatest benefit may be realized by grouping plants into IFG's having similar K_C values for periods of establishment, full canopy cover, and quiescence rather than just a single, season-wide average.

Water Use Efficiency

The equation used by Jarrell et al. (1983), Knox (1989), and Warsaw et al. (2009a and 2009b) to calculate WUE considers volume of water applied over the course of an entire production cycle for container-grown ornamental shrubs. However, because plants in the 2010 season were over-irrigated in the current study, WUE could be grossly underestimated in lower-use or smaller plants. Consequently, we used:

$$\text{WUE} = \text{GII (cm)} / [\text{taxon specific DWU } (\text{L}\cdot\text{container}^{-1})].$$

where GII= growth index increase from beginning of the season to the final measurement. This represents a sort of “potential” WUE as it shows how efficient plants would have been if only their required DWU had been applied as irrigation.

In 2009, the low water use taxa *A. arbutifolia* 'Brilliantissima', *I. virginica* 'Morton', and *T. plicata* 'Grovepli' all exhibited higher WUE in the 100DWU treatment than the control (Table 1.3). These taxa also generally had a lower GII compared to higher water use taxa. Additionally, taxa can be ranked according to WUE by comparing differences between taxa within each treatment. Compared to the other taxa, *Physocarpus opulifolius* 'Seward' had high WUE across all treatments and was more water efficient in the 100-75-75 than both *C. sericea* 'Farrow' and *H. paniculata* 'Limelight'. It also had the highest WUE of any taxa in the 100-75 treatment. The three high water use taxa *H. paniculata* 'Limelight', *P. opulifolius* 'Seward', and *W. florida* 'Alexandra' did not differ in WUE for the control or 100 DWU treatments. *Cornus sericea* 'Farrow' also showed high WUE in the 100DWU treatment. In 2010, no differences in WUE between treatments occurred, and only one difference occurred between species. *Weigela florida* 'Alexandra' had greater WUE in the 100DWU treatment compared to *S. meyeri* 'Palibin'. Only *V. dentatum* 'Ralph Senior' showed a difference in WUE_{DW} where the 100-75 treatment was lower than all other treatments (Table 1.4).

Taxa with greater overall GI also tended to have higher WUE than those with lower GI. Similarly, Knox (1989) showed WUE as high as 1.67 for *Photinia* x*fraseri* Dress., a larger-growing taxa and as low as 0.58 for the smaller coniferous taxa, *Juniperus horizontalis* Moench 'Wiltonii'. In Texas, WUE of shrubs generally increased in species showing larger or denser canopies (Still and Davies, 1993). In contrast,

Table 1.3. Water use efficiency as growth index (GI) increase : sum of DWU for season (through final day of growth index measurement 2009: Day 124, 2010: Day 117) for eight shrubs grown in 10.2 L containers under four irrigation treatments beginning 11 June 2009 and 23 June 2010.

Taxa	Control[z]	100DWU	100-75	100-75-75
2009				
Aronia arbutifolia 'Brilliantissima'	0.491 B[y]bc[x]	0.676 Aa	0.610 ABab	0.562 ABab
Cornus sericea 'Farrow'	0.373 Acd	0.891 Aa	0.467 Abc	0.508 Ab
Hydrangea paniculata 'Limelight'	0.631 Aab	0.486 Aab	0.512 Abc	0.498 Ab
Itea virginica 'Morton'	0.338 Bcde	0.512 Aab	0.445 ABc	0.466 ABb
Physocarpus opulifolius 'Seward'	0.762 Aa	0.853 Aa	0.764 Aa	0.714 Aa
Spiraea media 'Darsnorm'	0.203 ABde	0.259 Ab	0.183 Bd	0.201 ABc
Thuja plicata 'Grovepli'	0.140 Be	0.242 Ab	0.207 ABd	0.175 ABc
Weigela florida 'Alexandra'	0.489 Abc	0.580 Aab	0.536 Abc	0.529 Aab
2010				
Hydrangea arborescens 'Abetwo'	0.621 Aa	0.782 Aab	0.411 Aa	0.916 Aa
Hydrangea paniculata 'Limelight'	0.742 Aa	0.630 Aab	0.374 Aa	0.997 Aa
Rhus aromatica 'Gro-Low'	0.983 Aa	0.770 Aab	0.623 Aa	1.009 Aa
Spiraea fritschiana 'Wilma'	0.495 Aa	0.368 Aab	0.599 Aa	0.805 Aa
Syringa meyeri 'Palibin'	0.563 Aa	0.289 Ab	0.792 Aa	0.550 Aa
Syringa x*hyacinthiflora* 'Evangeline'	0.157 Aa	0.373 Aab	0.316 Aa	0.370 Aa
Viburnum dentatum 'Ralph Senior'	0.821 Aa	0.750 Aab	0.999 Aa	0.617 Aa
Weigela florida 'Alexandra'	0.640 Aa	1.154 Aa	1.016 Aa	0.653 Aa

Table 1.3 (cont'd)

[z]Control = 19 mm$\cdot$application^{-1} (1.02 L$\cdot$day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on 2009) lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day in DWU treatments as necessary; 2010) highest DWU of the 8 taxa in each treatment replicate each day.

[y]Comparisons between means in each row are marked with capital letters. Means of the same letters are not different; Tukey's Test (α = 0.05), 2009: n = 18, 2010: n=3.

[x]Comparisons between means in each column are marked with lowercase letters. Means of the same letters are not different; Tukey's Test (α = 0.05), 2009: n = 18, 2010: n=3.

Warsaw et al. (2009a), using GI, attributed most differences in WUE to varying irrigation volumes. Warsaw, et al. (2009b) observed that three of four species had higher WUE in their most water limiting 100-75-75 treatment than the control, very similar to the findings of the current study. Roberts and Schnipke (1987) reported that among 5 species of *Acer*, those having the fastest growth rates also had the highest relative water demand (which was calculated the same way as WUE in the current study). These findings support the current study in which DWU irrigation or other plant-based metrics generally improved WUE compared to irrigation regimes not based on plant water demand.

Table 1.4. Top dry weight and dry weight water use efficiency ($WUEd_W$) (season change in top dry weight in grams : sum of DWU plus precipitation in kg) of three taxa collected at the termination of the study in 2010. Irrigation treatments were imposed for 131 d from 23 June to 31 October 2010.

	Treatment			
	Control[z]	100DWU	100-75	100-75-75
Rhus aromatica 'Gro-Low'				
Shoot Dry Weight (g)	146.7 A[y]	138.3 A	128.0 A	127.9 A
WUE_{dw} (g/kg)	1.78 A	1.31 A	1.31 A	2.55 A
Viburnum dentatum 'Ralph Senior'				
Shoot Dry Weight (g)	57.4 A	71.4 A	71.9 A	59.2 A
WUE_{dw} (g/kg)	1.62 A	1.75 A	2.26 B	1.21 A
Weigela florida 'Alexandra'				
Shoot Dry Weight (g)	156.4 A	143.8 A	149.0 A	165.3 A
WUE_{dw} (g/kg)	2.31 A	4.07 A	3.88 A	2.63 A

[z]Control = 19 mm·application^{-1} (1.02 L·day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day.

[y]Comparisons between means in each row are marked with capital letters. Means of the same letters are not different; Tukey's Test (α = 0.05), n=9.

Leachate Electrical Conductivity and pH

When using controlled-release fertilizer (CRF) on container-grown nursery crops, desirable substrate leachate EC levels range from 0.8 to 1.5 dS·m^{-1} during periods of active growth (Yeager, 2003). No differences were found in EC between treatments in any taxa except *T. plicata* 'Grovepli' on day 16 when leachate EC was higher in the

Figure 1.8. PourThru leachate electrical conductivity (EC) (dS·m^{-1}) for A) *Aronia arbutifolia* 'Brilliantissima', B) *Cornus sericea* 'Farrow', C) *Hydrangea paniculata* 'Limelight', D) *Itea virginica* 'Morton', E) *Physocarpus opulifolius* 'Seward', F) *Spiraea media* 'Darsnorm', G) *Thuja plicata* 'Grovepli', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers from 11 June (Day 1) to 14 October 2009 (Day 126).

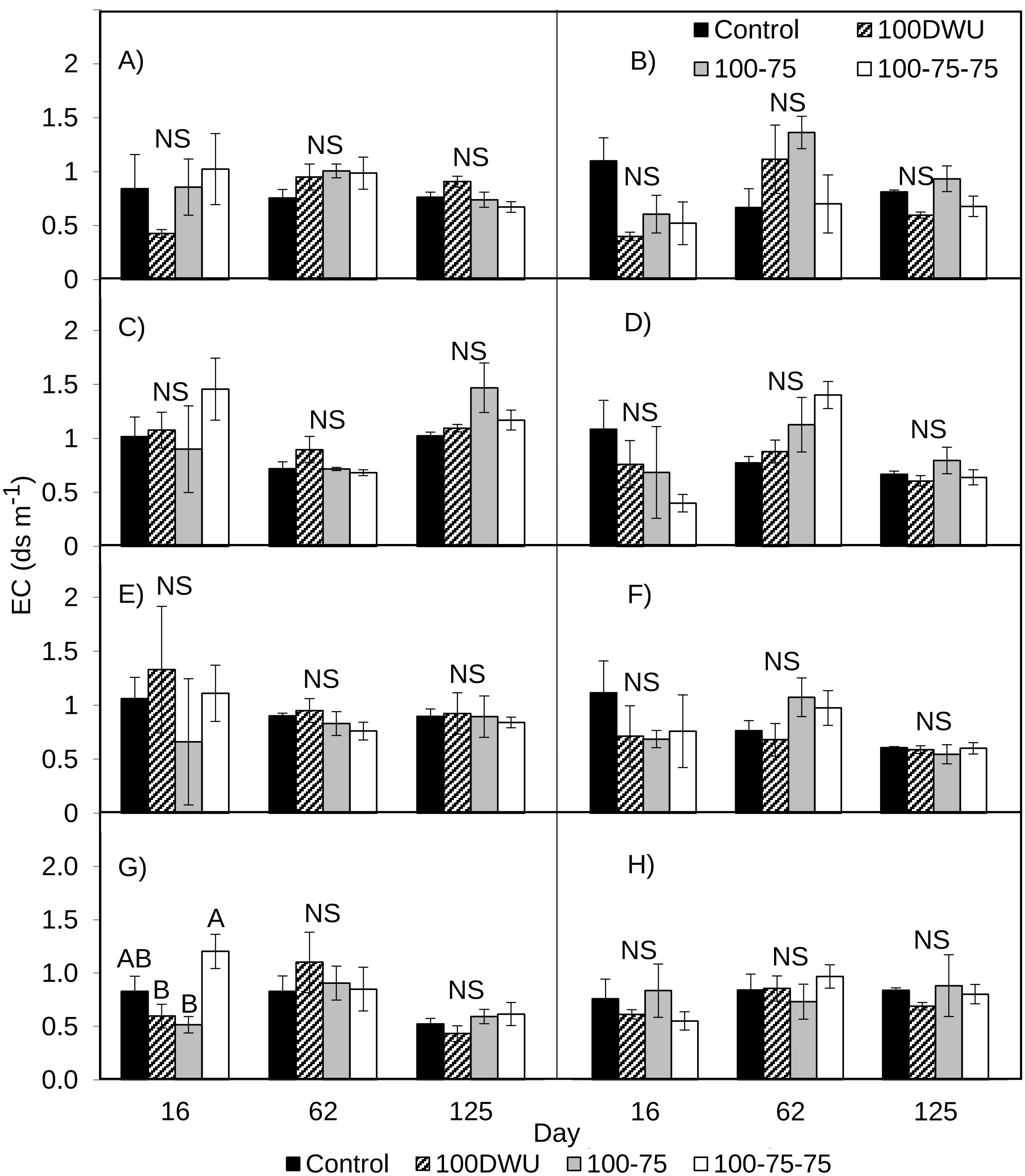


Figure 1.8 (cont'd)
Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day in DWU treatments as necessary.

100-75-75 treatment than the other DWU treatments (Figure 1.8). EC remained above the minimum recommended threshold of 0.8 dS·m^{-1} for all taxa throughout the experiment except *I. virginica* 'Morton' and *S. media* 'Darsnorm' on day 125. None exceeded the upper limits during the season. In 2010, EC was almost double the recommended levels on day 2 for all taxa except the *Syringa* species (Figure 1.9). By day 34, EC had fallen below the upper threshold of 1.5 in most taxa. The only difference in EC occurred on day 59 in *V. dentatum* 'Ralph Senior' when the control and 100-75-75 treatments were higher than the 100-75, which received more water than any other treatment. Of 24 shrubs studied, Warsaw et al. (2009a) reported few differences in EC except in the highest water treatment (control), which was higher than DWU-based treatments. Million et al. (2007) demonstrated that an EC of <0.5 dS·m^{-1} caused reductions in growth of *Viburnum odoratissimum* L. (high nutrient and water user); however, no treatment differences in GI or EC support this in the current study. Another source suggests that EC of 0.5 dS·m^{-1} is adequate late in the growing season (Bilderback et al., 1999), which is close to the levels observed for 2010 in the current study. Overall, end-of-season EC levels were likely lower in 2010 than 2009 because

Figure 1.9. PourThru leachate electrical conductivity (EC) ($dS \cdot m^{-1}$) for A) *Hydrangea arborescens* ‘Abetwo’, B) *Hydrangea paniculata* ‘Limelight’, C) *Rhus aromatica* ‘Gro-Low’, D) *Spiraea fritschiana* ‘Wilma’, E) *Syringa meyeri* ‘Palibin’, F) *Syringa* x*hyacinthiflora* ‘Evangeline’, G) *Viburnum dentatum* ‘Ralph Senior’, and H) *Weigela florida* ‘Alexandra’ grown in 10.2 L containers from 23 June (Day 1) to 31 October (Day 131).

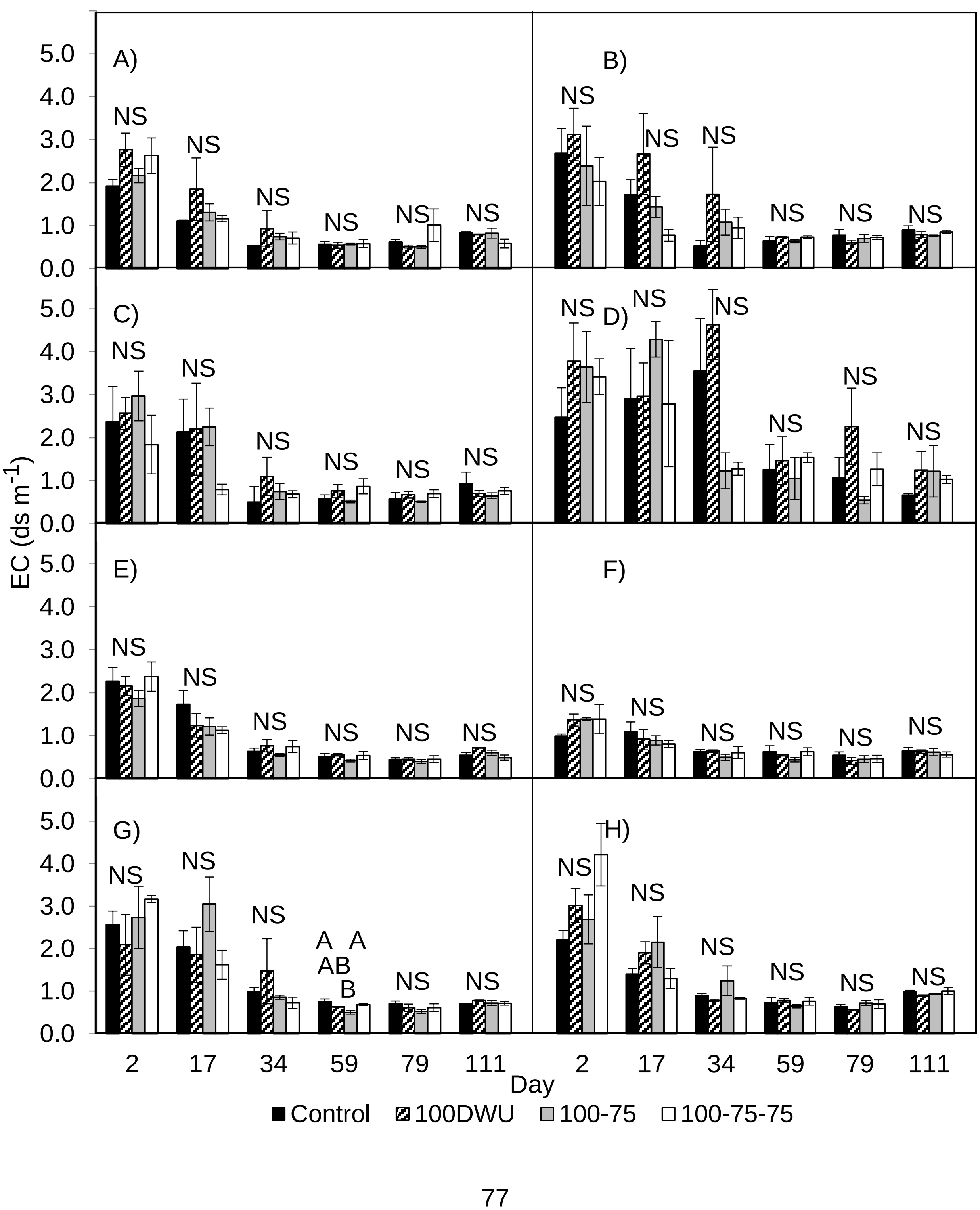


Figure 1.9 (cont'd)
Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, $\alpha = 0.05$). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day.

all plants were irrigated at the same level as the highest user which resulted in leaching from the lower users. Excess irrigation leaches both salts and nutrients from substrates and can lead to plant nutrient deficiencies (Bilderback, et al., 1999) and increased nutrient loading in effluent, which leads to water quality concerns (Warsaw et al., 2009b). Although not observed in this study or by Warsaw et al. (2009a), EC can reach potentially harmful levels in plants subjected to low-leaching irrigation regimes; therefore, EC should monitored regularly under these conditions.

Substrate leachate pH remained fairly consistent in 2009, but several differences occurred between treatments (Figure 1.10). The control exceeded pH of the 100-75 treatment on day 62 for *C. sericea* 'Farrow'. On days 62 and 125, the control had higher pH than the 100-75-75 treatment for *I. virginica* 'Morton'. The control and 100DWU were greater than the 100-75-75 treatment on day 125 for *I. virginica* 'Morton' and on day 62 for *W. florida* 'Alexandra'. For every observed difference in pH, the control was higher than at least one DWU treatment. In 2010, similar results were observed when *Syringa meyeri* 'Palibin' showed higher pH in the 100DWU treatment than the control on day 79 and higher pH in the 100DWU and 100-75 treatments than 100-75-75 treatment on day 111. Both the 100DWU and 100-75-75 treatments received more water than those with low pH. In addition, pH increased throughout the

Figure 1.10. Leachate pH for A) *Aronia arbutifolia* 'Brilliantissima', B) *Cornus sericea* 'Farrow', C) *Hydrangea paniculata* 'Limelight', D) *Itea virginica* 'Morton', E) *Physocarpus opulifolius* 'Seward', F) *Spiraea media* 'Darsnorm', G) *Thuja plicata* 'Grovepli', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers from 11 June (Day 1) to 14 October 2009 (Day 126).

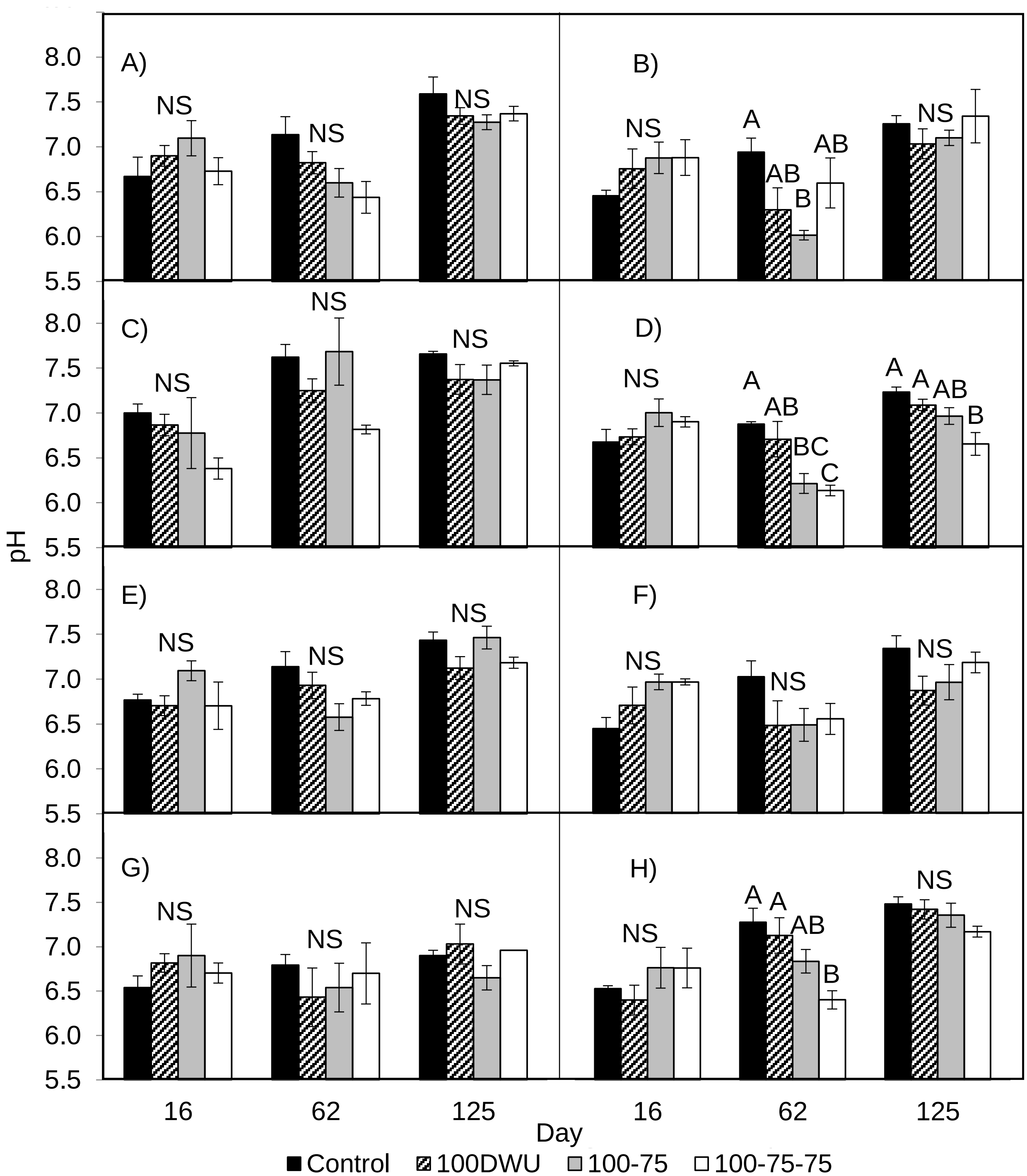


Figure 1.10 (cont'd)
Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, $\alpha = 0.05$). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day in DWU treatments as necessary.

2010 season. The last known irrigation water test at the MSU HTRC was taken in 2007 by Warsaw et al. (2009a). They reported mildly basic pH of 7.7, which was close to the final leachate pH observed in nearly every treatment-taxa combination by the end of the study. The basicity of the irrigation water, combined with known high alkalinity in the area, likely contributed to this increase in substrate pH. Burnett and van Iersel (2008) reported similar increase in pH when using basic, alkaline water during an irrigation study with herbaceous perennials.

Figure 1.11. Leachate pH for A) *Hydrangea arborescens* 'Abetwo', B) *Hydrangea paniculata* 'Limelight', C) *Rhus aromatica* 'Gro-Low', D) *Spiraea fritschiana* 'Wilma', E) *Syringa meyeri* 'Palibin', F) *Syringa* x*hyacinthiflora* 'Evangeline', G) *Viburnum dentatum* 'Ralph Senior', and H) *Weigela florida* 'Alexandra' grown in 10.2 L containers from 23 June (Day 1) to 31 October 2010 (Day 131).

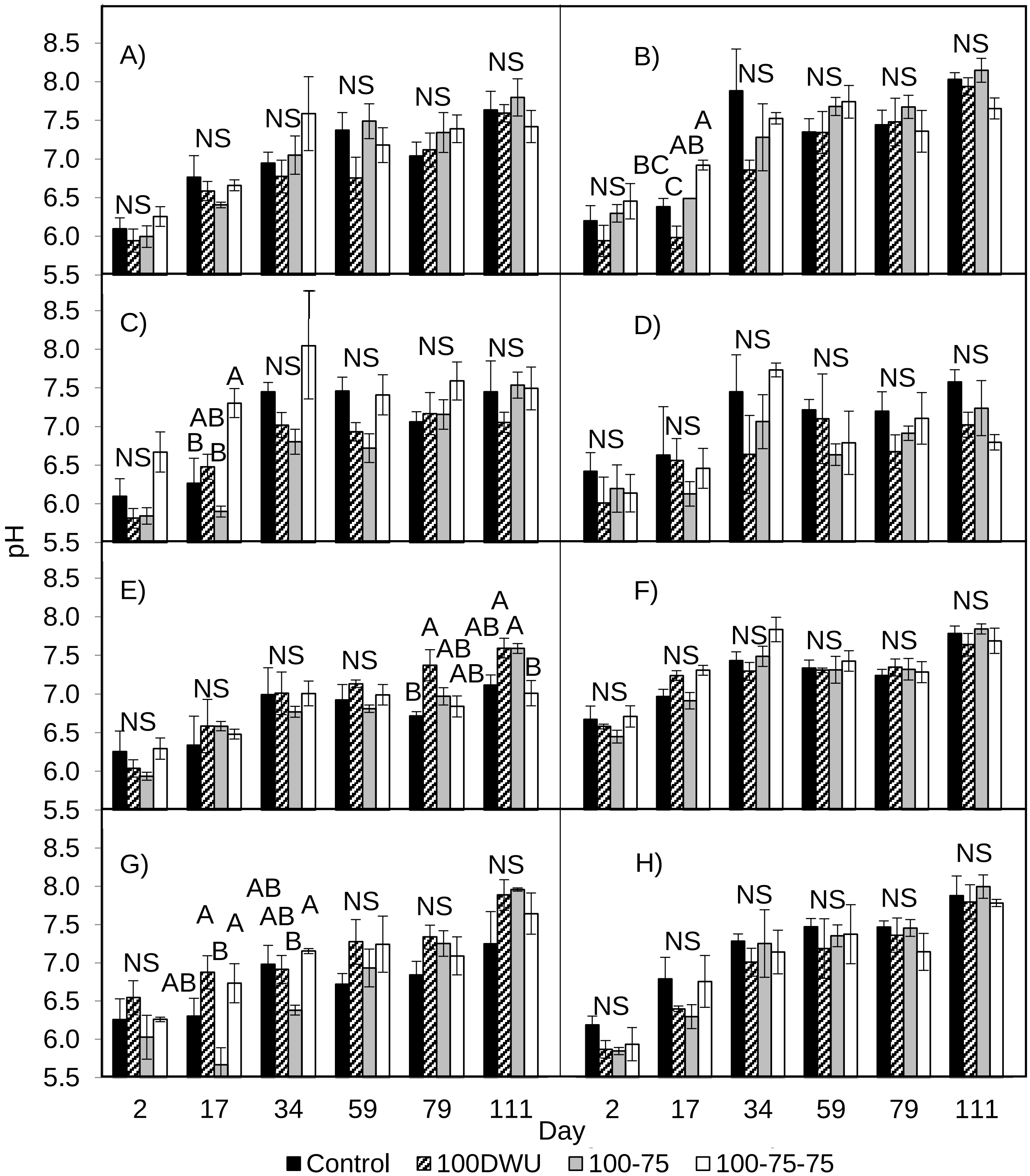


Figure 1.11 (cont'd)
Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, $\alpha = 0.05$). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day.

Foliar Nutrient Analysis

Analysis of foliar nutrient levels revealed higher %P and / or %K in at least one of the DWU treatments compared to the control for every taxa on the second sampling date (Table 1.5) in 2009. Additionally, *I. virginica* 'Morton' showed higher %P in the 100-75-75 treatment than the control on day 63. Since the control received the most water of any irrigation treatment in 2009, this difference could be attributable to either high irrigation levels leaching nutrients from the substrate or nutrient dilution within the plant, or a combination of both. Although no taxa fell below the minimum recommended foliar %N level (Plank, 2008) during 2009, %K was low in the control on day 90 in every taxa except *S. media* 'Darsnorm'. Additionally, %P was low in the largest growing taxa, *H. paniculata* 'Limelight' on day 90. However, no visual nutrient deficiency symptoms were observed, and plant quality appeared acceptable in every taxa. In 2010, only one difference occurred where foliar %N was lower in the 100-75 than 100DWU treatment for *H. paniculata* 'Limelight'. Since the 100-75 treatment received highest irrigation

Table 1.5. Foliar nutrient content (% dry wt.) sampled on days 63 and 90 of five taxa grown in 10.2 L containers and subject to four irrigation treatments from 11 June (Day 1) to 14 October 2009 (Day 126).

	Foliar Nutrient Content				Recommended
	Control[z]	100DWU	100-75	100-75-75	Range[y]
		Hydrangea paniculata 'Limelight'			
Day 63					
N (%)	2.87 A[y]	2.88 A	2.99 A	2.96 A	2 - 4.5
P (%)	0.24 A	0.29 A	0.30 A	0.29 A	0.2 - 0.6
K (%)	1.65 A	2.23 A	2.07 A	2.07 A	1.5 - 3.5
Day 90					
N (%)	2.24 A	2.35 A	2.38 A	2.31 A	
P (%)	0.14 B	0.17 AB	0.18 A	0.17 AB	
K (%)	0.41 B	0.65 A	0.61 AB	0.67 A	
		Itea virginica 'Morton'			
Day 63					
N (%)	2.50 A	2.69 A	2.46 A	2.65 A	2 - 4.5
P (%)	0.22 A	0.22 A	0.22 A	0.24 A	0.2 - 0.6
K (%)	0.65 A	0.55 A	0.58 A	0.66 A	1.5 - 3.5
Day 90					
N (%)	2.37 A	2.74 A	2.59 A	2.55 A	
P (%)	0.16 B	0.20 AB	0.20 AB	0.21 A	
K (%)	0.48 A	0.53 A	0.54 A	0.55 A	
		Physocarpus opulifolius 'Seward'			
Day 63					
N (%)	3.19 A	3.19 A	3.19 A	3.33 A	2 - 4.5
P (%)	0.31 B	0.37 A	0.37 A	0.39 A	0.2 - 0.6
K (%)	1.09 B	1.46 A	1.59 A	1.66 A	1.5 - 3.5
Day 90					
N (%)	2.15 A	2.20 A	2.28 A	2.28 A	
P (%)	0.21 B	0.23 AB	0.25 A	0.24 A	
K (%)	0.38 B	0.41 A	0.45 A	0.42 A	
		Spiraea media 'Darsnorm'			
Day 63					
N (%)	2.27 A	2.38 A	2.23 A	2.42 A	2 - 4.5
P (%)	0.63 A	0.67 A	0.66 A	0.66 A	0.2 - 0.6
K (%)	1.26 A	1.63 A	1.66 A	1.64 A	1.5 - 3.5
Day 90					
N (%)	2.50 A	2.70 A	2.63 A	2.74 A	
P (%)	0.72 B	0.81 AB	0.87 A	0.81 AB	
K (%)	1.14 B	1.39 AB	1.52 A	1.32 AB	

Table 1.5 (cont'd)

	Foliar Nutrient Content (continued)				Recommended
	Control	100DWU	100-75	100-75-75	Range[y]
		Weigela florida 'Alexandra'			
Day 63					2 - 4.5
N (%)	2.05 A	2.12 A	2.20 A	2.21 A	0.2 - 0.6
P (%)	0.34 A	0.37 A	0.38 A	0.39 A	1.5 - 3.5
K (%)	1.91 B	2.38 A	2.31 AB	2.55 A	
Day 90					
N (%)	2.18 A	2.02 A	2.06 A	2.05 A	
P (%)	0.30 A	0.35 A	0.38 A	0.40 A	
K (%)	0.98 A	1.18 A	1.11 A	1.21 A	

[z]Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, $\alpha = 0.05$). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period with remaining water requirement supplied by hand each day in DWU treatments as necessary.

[y]Nutrient recommendations for woody ornamental plants obtained from Plank (2008).

applications in 2010, this also likely caused the %N reduction in this treatment. Many nutrients were below recommended levels on day 64, even in the 100-75-75 treatment, which received less water than any other treatment. Since cumulative precipitation was lower in 2010 than 2009 (Figure 1.3), this cannot likely be attributed to leaching from rainfall. However, average daily temperature was 19.82^{o}C between days 1 and 64 in 2010 compared to 17.94^{o}C the same calendar dates in 2009. Consequently, the release rate of nutrients from the CRF was likely higher, contributing to this relatively early seasonal depletion of foliar nutrients.

Table 1.6. Foliar nutrient content (% dry wt.) sampled on days 36 and 64 of six taxa grown in 10.2 L containers and subject to four irrigation treatments from 23 June (Day 1) to 31 October 2010 (Day 131).

	Foliar Nutrient Content				Recommended
	Control[z]	100DWU	100-75	100-75-75	Range[y]
		Hydrangea arborescens 'Abetwo'			
Day 36					
N (%)	2.69 A[y]	2.73 A	2.72 A	2.60 A	2 - 4.5
P (%)	0.26 A	0.32 A	0.32 A	0.32 A	0.2 - 0.6
K (%)	1.09 A	1.47 A	1.46 A	1.44 A	1.5 - 3.5
Day 64					
N (%)	1.72 A	1.58 A	1.59 A	1.33 A	
P (%)	0.18 A	0.21 A	0.20 A	0.23 A	
K (%)	1.09 A	1.47 A	1.46 A	1.44 A	
		Hydrangea paniculata 'Limelight'			
Day 36					
N (%)	2.60 AB	2.79 A	2.40 B	2.52 AB	2 - 4.5
P (%)	0.25 A	0.27 A	0.26 A	0.29 A	0.2 - 0.6
K (%)	1.56 A	1.68 A	1.57 A	1.81 A	1.5 - 3.5
Day 64					
N (%)	1.72 A	1.58 A	1.59 A	1.33 A	
P (%)	0.17 A	0.16 A	0.15 A	0.18 A	
K (%)	0.88 A	0.92 A	0.74 A	0.95 A	
		Rhus aromatica 'Gro-low'			
Day 36					
N (%)	1.95 A	2.02 A	2.05 A	1.84 A	2 - 4.5
P (%)	0.29 A	0.30 A	0.30 A	0.29 A	0.2 - 0.6
K (%)	1.84 A	2.02 A	2.05 A	1.84 A	1.5 - 3.5
Day 64					
N (%)	1.76 A	1.65 A	1.79 A	1.55 A	
P (%)	0.20 A	0.20 A	0.20 A	0.19 A	
K (%)	0.52 A	0.72 A	0.60 A	0.54 A	
		Spiraea fritschiana 'Wilma'			
Day 36					
N (%)	3.17 A	3.17 A	3.00 A	3.08 A	2 - 4.5
P (%)	0.47 A	0.41 A	0.51 A	0.43 A	0.2 - 0.6
K (%)	1.26 A	1.12 A	1.09 A	1.23 A	1.5 - 3.5
Day 64					
N (%)	2.81 A	2.66 A	2.61 A	2.51 A	
P (%)	0.34 A	0.33 A	0.34 A	0.34 A	
K (%)	1.04 A	1.01 A	0.88 A	1.09 A	

Table 1.6 (cont'd)

	Foliar Nutrient Content (continued)				Recommended
	Control[z]	100DWU	100-75	100-75-75	Range[y]
			Viburnum dentatum 'Ralph Senior'		
Day 36					
N (%)	2.18 A	2.23 A	2.13 A	2.11 A	2 - 4.5
P (%)	0.31 A	0.31 A	0.32 A	0.31 A	0.2 - 0.6
K (%)	1.61 A	1.85 A	1.81 A	1.93 A	1.5 - 3.5
Day 64					
N (%)	2.37 A	2.32 A	1.80 B	2.31 A	
P (%)	0.31 A	0.26 A	0.25 A	0.29 A	
K (%)	1.58 A	1.45 A	1.39 A	1.34 A	
			Weigela florida 'Alexandra'		
Day 36					2 - 4.5
N (%)	2.12 A	1.98 A	1.82 A	1.94 A	0.2 - 0.6
P (%)	0.37 A	0.38 A	0.33 A	0.39 A	1.5 - 3.5
K (%)	1.71 A	1.91 A	1.67 A	1.81 A	
Day 64					
N (%)	1.89 A	1.70 A	1.70 A	1.69 A	
P (%)	0.29 A	0.29 A	0.26 A	0.29 A	
K (%)	1.13 A	1.37 A	1.19 A	1.26 A	

[z]Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Each day was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. NS = not significant. n=3. Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day.

[y]Nutrient recommendations for woody ornamental plants obtained from Plank (2008).

Similar to the current study, reductions in foliar nutrient concentrations occurred at a higher irrigation leaching fraction (LF) of 0.4 compared to 0.1 in *Ligustrum texanum*, which was ascribed to both nutrient dilution within plants at higher LF's and lower K quantities leaching from the substrate (Jarrell et al., 1983). Tyler et al. (1996) also showed that a high LF of 0.4 - 0.6 increased N utilization in plant shoots. Additionally, P content in tops of *Cotoneaster dammeri* C.K. Schneid. 'Skogholm' fertilized with CRF's decreased with increasing irrigation volume (Groves et al., 1998), which supports the findings in the current study that higher irrigation rates tend to lower foliar nutrient contents.

Conclusions

Less water was applied to plants in DWU water-based treatments in 2009, yet growth was not negatively impacted compared to the control, nursery standard irrigation rate of 19 mm·container·day^{-1}. *Hydrangea paniculata* 'Limelight', a high water user, grew larger in the 100DWU treatment than the control. When sensors were employed for real-time calculation of DWU in 2010, the system determined the highest water user of eight taxa each day to apply that DWU to the entire irrigation treatment replicate. This resulted in over-watering of the other seven taxa, and consequently, more water was applied in the 100DWU and 100-75 treatments than either the control or 100-75-75. In 2010, the highest overall water user, *H. paniculata* 'Limelight' was 10% smaller than the control in the 100-75-75, though it was the same size as the control in the milder deficit of the 100-75 treatment. However, all plants maintained acceptable size, appearance, and quality so that an average consumer would likely not perceive the growth difference. Plants in low-volume treatments, particularly those that are smaller or slower-growing, used water more efficiently than the higher volume treatments. Additionally, substrate leachate pH generally increased over the course of production seasons and was higher in the control irrigation rate in several instances. Foliar nutrient %P and %K was higher in DWU-based treatments than the control in many cases indicating that DWU-based irrigation regimes conserve nutrients. Reduced NO_3^--N and PO_4^{3-}-P loading in effluent has also been reported in irrigation treatments (Chapter 3; Warsaw et al., 2009b). Consequently, producers can reduce water inputs and manage nutrition more effectively with DWU-based irrigation regimes.

Adding to the convenience of scheduling irrigation in real-time, valuable DWU and K_C data obtained by the system showed marked fluctuations from day to day for container-grown shrubs and monthly K_C changes. Seasonal K_C for 10 new taxa add to the growing number of published K_C values for container-grown woody ornamentals (Warsaw et al. 2009a and b; Schuch and Burger, 1997; Burger et al.,1987) further helping to establish indicator species for low, moderate, and high water use classifications that prove useful when grouping plants into irrigation blocks with similar water needs. Additionally, K_C increases during establishment of young plants and generally climaxes midsummer through autumn for temperate, cold-hardy ornamental shrubs produced in containers. Therefore, newly-published K_C information should include separate values for ornamentals during establishment, maximum seasonal growth or full canopy cover, and quiescence to match K_C during each period, not just over the course of the entire season.

Grower-friendly systems are now being tested on commercial operations that permit multiple sensor inputs in a multi-hop, self-configuring network capable of transmitting data wirelessly managed through intuitive, yet powerful software (Lea-Cox et al., 2008; Lea-cox et al., 2013). Used alone, these systems provide growers with additional data to make more informed scheduling decisions on their own (Chappell et al., 2013). However, they also permit full automation of the irrigation scheduling process and have shown to reduce irrigation while increasing growth of ornamental trees in pot-in-pot production compared to “experience”-based irrigation (Belayneh et al., 2013). Although widespread adoption of these systems may take several years, monitoring of every ornamental crop produced at most nurseries will not likely be economically feasible. Therefore, knowledge of relative water use classifications, derived by K_C or other means, will be an essential part of effective sensor integration into existing irrigation infrastructure to help growers maximize water use savings and achieve greater crop profitability.

APPENDIX

Table A-1. Monthly crop coefficient (K_C) from 11 June (Day 1) to 14 October 2009 (Day 126) for 8 shrub taxa grown in 10.2 L containers.

	Crop Coefficient			
Month	Control[z]	100DWU	100-75	100-75-75
		Aronia arbutifolia 'Brilliantissima'		
June	2.40 Ab	2.80 Aab	3.14 Aa	2.16 Ab
July	2.42 Ab	2.23 Ab	2.02 Aa	2.32 Ab
August	4.17 Aa	4.05 Aa	3.76 Aa	3.56 Ab
September	3.78 Aab	3.09 Aab	3.39 Aa	2.76 Ab
October	5.22 Aa	3.74 Aab	3.50 Aa	5.13 Aa
Season	3.60 A	3.35 A	3.22 A	3.18 A
		Cornus sericea 'Farrow'		
June	2.58 Ab	2.32 Abc	2.34 Ac	2.12 Ac
July	2.84 Ab	1.96 Bc	2.52 ABc	2.60 ABc
August	5.88 Aa	4.82 Aa	6.52 Aa	4.56 Ab
September	5.28 Aab	4.64 Aa	3.95 Abc	5.71 Aab
October	7.35 Aa	4.19 Aab	5.87 Aab	6.62 Aa
Season	4.80 A	3.71 A	4.09 A	4.12 A
		Hydrangea paniculata 'Limelight'		
June	2.12 Ac	2.02 Ac	2.42 Ac	2.11 Ac
July	3.55 Abc	3.48 Ac	2.53 Bb	3.11 ABc
August	5.72 Bab	8.03 Aa	7.24 ABa	6.08 Bb
September	5.92 Aa	5.83 Ab	5.84 Aa	5.78 Ab
October	6.75 Aa	8.35 Aa	7.25 Aa	8.96 Aa
Season	4.92 B	6.07 A	5.35 AB	5.31 AB
		Itea virginica 'Morton'		
June	2.00 ABb	1.42 Bc	3.05 Aab	2.69 ABa
July	2.57 Ab	2.40 Abc	2.21 Ab	2.52 Aa
August	4.42 Aab	4.93 Aa	3.56 Aab	3.47 Aa
September	2.61 Ab	3.65 Aab	4.23 Aa	3.15 Aa
October	6.02 Aa	3.05 Babc	4.22 ABa	4.13 ABa
Season	3.71 A	3.55 A	3.45 A	3.21 A
		Physocarpus opulifolius 'Seward'		
June	2.43 Ac	2.79 Ab	2.25 Ab	2.24 Ab
July	2.95 Abc	2.44 Ab	2.33 Ab	2.34 Ab
August	5.87 Aa	6.59 Aa	5.82 Aa	5.53 Aa
September	4.59 Aab	5.20 Aa	4.44 Aa	6.35 Aa
October	5.74 Aa	6.25 Aa	5.75 Aa	7.13 Aa
Season	4.56 A	5.06 A	4.29 A	4.77 A

Table A-1 (cont'd)

	Crop Coefficient (continued)			
Month	Control[z]	100DWU	100-75	100-75-75
		Spiraea media 'Darsnorm'		
June	2.14 Ab	2.10 Ab	3.01 Abc	2.88 Abc
July	2.85 Ab	2.19 ABb	2.30 ABc	1.97 Bc
August	5.05 Aa	4.39 Aa	4.89 Aab	3.49 Abc
September	2.88 Ab	4.12 Aa	3.31 Abc	4.03 Ab
October	5.92 Aa	3.67 Aab	5.47 Aa	6.45 Aa
Season	3.94 A	3.51 A	3.92 A	3.78 A
		Thuja plicata 'Grovepli'		
June	2.33 ABb	2.14 Ba	2.68 ABab	3.74 Ab
July	2.72 Aab	2.59 Aa	2.25 Ab	2.79 Ab
August	4.42 Aab	4.06 Aa	3.30 Aab	3.26 Ab
September	5.16 Aa	4.08 Aa	2.74 Aab	3.22 Ab
October	4.99 Aa	3.25 Aa	3.87 Aa	5.62 Aa
Season	3.97 A	3.39 AB	3.00 B	3.97 A
		Weigela florida 'Alexandra'		
June	2.40 ABc	1.64 Bb	2.27 ABb	2.88 Acd
July	2.91 Abc	2.44 ABb	2.18 Bb	2.65 ABd
August	4.43 Aab	4.89 Aa	3.97 Aab	4.37 Abc
September	3.48 Babc	5.24 ABa	4.37 ABa	5.38 Ab
October	4.73 Ba	5.92 ABa	5.31 ABa	7.48 Aa
Season	3.69 B	4.30 AB	3.65 B	4.70 A

[z]Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on lowest DWU of the 8 taxa during each measurement period; remaining water requirement supplied by hand each day as necessary. Daily ET_0 values for calculation of K_c obtained from the Enviro-weather Automated Weather Station Network.

[y]Separation of means performed with Tukey's Test (α = 0.05). Means followed by the same letters within rows are not different. Jun, Jul, Sep, and Oct: n=18, Aug: n=36. Season: n=108.

[x]Comparisons between means in each column are marked with lowercase letters. Means of the same letters are not different; Tukey's Test (α = 0.05). Jun, Jul, Sep, and Oct: n=18, Aug: n=36.

Table A-2. Monthly crop coefficient (K_C) from 23 June (Day 1) to 31 October 2010 (Day 131) for 8 shrub taxa grown in 10.2 L containers.

	Crop Coefficient			
Month	Control^z	100DWU	100-75	100-75-75
	Hydrangea arborescens'Abetwo'			
June	1.56 ABb	1.55 ABb	1.96 Ac	0.79 Bb
July	3.69 Aa	2.26 Bb	4.73 Ab	1.92 Bab
August	5.07 Ba	3.83 BCa	7.83 Aa	2.92 Ca
September	4.82 Ba	4.00 BCa	6.90 Aa	2.94 Ca
October	4.09 Ba	4.25 Ba	6.24 Aab	2.39 Cab
Season	4.24 B	3.51 C	6.09 A	2.51 D
	Hydrangea paniculata 'Limelight'			
June	1.91 ABb	2.08 ABb	2.70 Ab	1.27 Bb
July	3.94 Ba	5.13 ABa	6.67 Aa	3.81 Ba
August	4.79 Ba	6.82 Aa	7.92 Aa	5.03 Ba
September	4.99 ABa	6.14 ABa	6.89 Aa	4.58 Ba
October	4.71 ABa	4.90 ABa	6.21 Aa	3.51 Bab
Season	4.41 C	5.46 B	6.64 A	4.04 C
	Rhus aromatica 'Gro-low'			
June	2.26 Ac	1.96 ABb	1.99 ABc	0.95 Bb
July	4.67 Aab	3.66 ABa	4.90 Aab	2.38 Bab
August	5.67 Aa	4.67 ABa	5.66 Aa	3.76 Ba
September	4.50 ABab	4.43 ABa	4.85 Aab	3.24 Ba
October	2.27 ABc	3.69 Aa	3.82 Ab	2.49 Bab
Season	4.21 A	3.98 A	4.63 A	2.87 B
	Spiraea fritschiana 'Wilma'			
June	1.94 Ab	1.84 Ac	1.42 ABb	0.58 Bc
July	3.83 Aa	3.92 Aab	3.19 Aa	1.82 Bab
August	2.45 Bab	4.87 Aa	3.58 Ba	2.38 Ba
September	3.00 Bab	4.46 Aa	2.44 Bab	1.80 Bab
October	2.24 Ab	2.44 Abc	1.85 ABb	1.21 Bbc
Season	2.76 B	3.74 A	2.70 B	1.71 C
	Syringa meyeri 'Palibin'			
June	1.11 Aab	1.60 Ac	0.89 Ab	1.06 Aa
July	1.77 Aa	1.72 Abc	0.98 Bb	1.39 ABa
August	0.58 Cb	3.02 Aab	1.05 BCb	1.65 Ba
September	1.95 Aa	3.15 Aa	1.97 Aa	2.08 Aa
October	1.69 Bab	3.02 Aab	1.54 Bab	2.34 ABa
Season	1.45 BC	2.67 A	1.31 C	1.83 B

Table A-2 (cont'd)

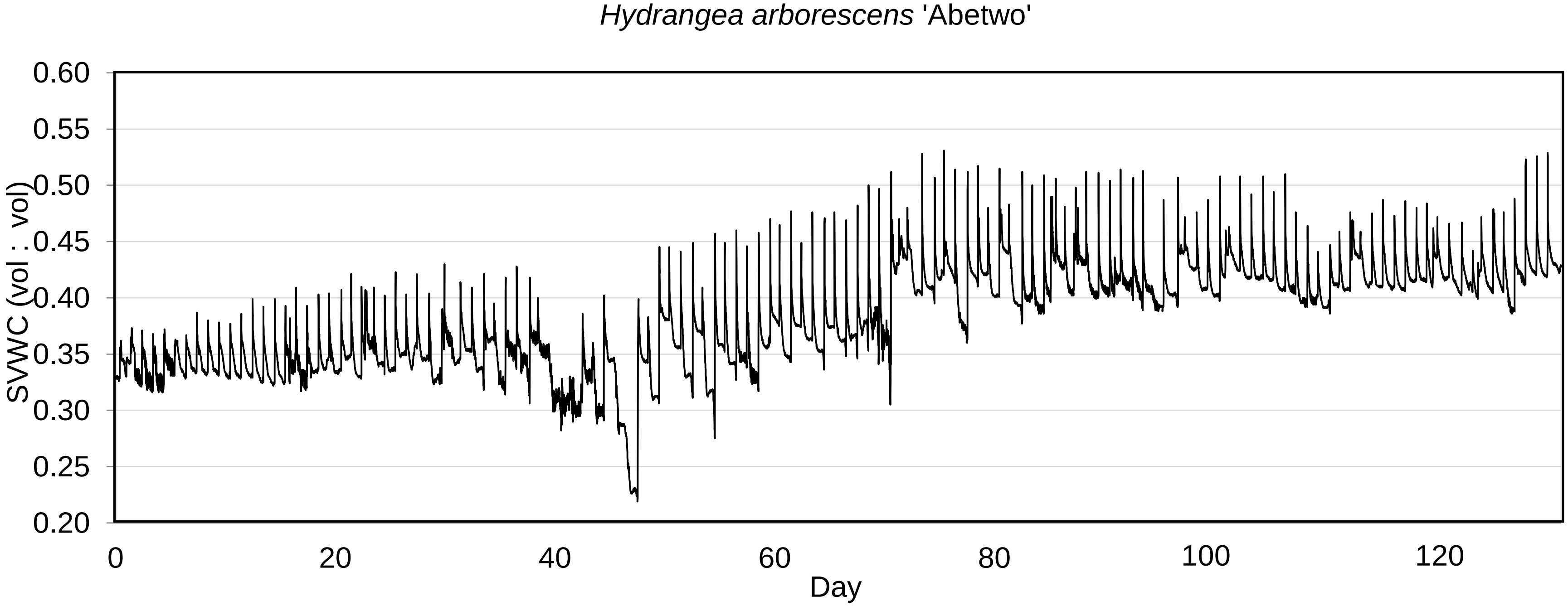
	Crop Coefficient (continued)			
Month	Control[z]	100DWU	100-75	100-75-75
	Syringa xhyacinthiflora 'Evangeline'			
June	2.02 Ab	0.81 Ba	1.06 Ba	1.01 Ba
July	3.43 Aab	0.82 Ba	1.25 Ba	1.20 Ba
August	3.53 Aab	0.86 Ba	1.24 Ba	0.92 Ba
September	3.91 Aab	0.92 Ba	1.39 Ba	0.82 Ba
October	4.50 Aa	1.07 Ba	1.49 Ba	1.19 Ba
Season	3.76 A	0.92 B	1.33 B	1.03 B
	Viburnum dentatum 'Ralph Senior'			
June	0.98 Ab	1.43 Ab	0.74 Ac	1.56 Aa
July	1.41 Bb	1.74 Bb	1.24 Bbc	2.39 Aa
August	2.20 Aa	2.23 Aab	1.73 Aab	2.00 Aa
September	2.10 Aa	2.72 Aab	2.16 Aa	2.40 Aa
October	2.23 Ba	3.52 Aa	1.87 Bab	2.44 Ba
Season	1.96 BC	2.50 A	1.69 C	2.26 AB
	Weigela florida 'Alexandra'			
June	1.45 Ac	0.83 Ac	1.09 Ab	1.47 Ab
July	2.75 Abc	1.33 Bbc	1.78 Bab	2.78 Aab
August	4.53 Aa	2.33 Bab	2.18 Ba	4.62 Aa
September	4.14 Aab	2.72 BCa	2.35 Ca	3.90 ABa
October	3.83 Aab	1.91 Babc	2.21 Ba	3.38 Aab
Season	3.69 A	1.99 B	2.08 B	3.57 A

[z]Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Overhead irrigation scheduling based on highest DWU of the 8 taxa in each treatment replicate each day. Daily ET_0 values for calculation of K_C obtained from the Enviro-weather Automated Weather Station Network.

[y]Separation of means performed with Tukey's Test (α = 0.05). Means followed by the same letters within rows are not different. Jun: n=24 (except 100-75-75 treatment, n=16). Jul, Aug, and Oct: n= 93 (except 100-75-75, n= 62). Sep: n= 90 (except 100-75-75, n=60). Season: n=393.

[x]Comparisons between means in each column are marked with lowercase letters. Means of the same letters are not different; Tukey's Test (α = 0.05). Jun: n=24 (except 100-75-75 treatment, n=16). Jul, Aug, and Oct: n= 93 (except 100-75-75, n= 62). Sep: n= 90 (except 100-75-75, n=60).

Figure A-1. Substrate volumetric water content (SVWC) (vol : vol) from time capacitance sensor measurements taken every 15 min from 23 Jun (Day 1) to 1 November (Day 131). Representative plant chosen is *Hydrangea arborescens* 'Abetwo' growing in a 10.2 L container from the 100DWU treatment. Peaks represent daily irrigation events.



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CHAPTER 2

IRRIGATING BASED ON DAILY WATER USE REDUCES NURSERY EFFLUENT VOLUME AND NUTRIENT LOAD WITHOUT REDUCING GROWTH OF FOUR CONIFERS

Abstract

The objectives of this study were to quantify irrigation volume, runoff volume and nutrient content, and plant growth of container-grown conifers when subjected to a daily water use (DWU)- based irrigation regime in contrast to a standard irrigation rate. Four conifer taxa were grown in 10.2-L (#3) containers subjected to four irrigation treatments from 23 June through 16 October 2009 and 6 June through 31 October 2010, based either on daily water use (DWU) or a control (nursery standard) application rate. The plants studied were: 1) *Chamaecyparis obtusa* Sieb. & Zucc. 'Filicoides', 2) *Chamaecyparis pisifera* (Sieb. & Zucc.) Endl. 'Sungold', 3) *Thuja occidentalis* L. 'Holmstrup', and 4) *Thuja plicata* D. Donn 'Zebrina'. The four irrigation treatments applied were: 1) control application of 19 $mm \cdot ha^{-1} \cdot d^{-1}$, 2) irrigation applied to replace 100% DWU (100DWU) each day, 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle (100-75), and 4) a 3-day application cycle replacing 100% DWU the first day and 75% DWU on the second and third days (100-75-75). Irrigation treatments did not affect plant growth index {GI= [(H + W_{NS} + W_{EW}) / 3]} in 2009. In 2010, 100DWU increased growth index of *C. obtusa* 'Filicoides' relative to control plants. Season (114 d) total water applied for 100DWU, 100-75, and 100-75-75 treatments was 22%, 32%, and 56% less, respectively, than the control of 117 $L \cdot container^{-1}$ in 2009 and 24%, 18%, and 24% less than the control of 165 $L \cdot container^{-1}$ in 2010 (147 d). Scheduling irrigation based on DWU reduced effluent volumes collected from growing areas and NO_3^- -N and PO_4^{3-}-P load when compared to the control. Consequently, irrigating based on DWU reduced water applications and NO_3^- -

N and PO_4^{3-}-P losses while also producing plants of equal or greater size than control plants.

Introduction

Producers must irrigate container-grown nursery plants frequently, often multiple times daily, because of container volume limitations and substrate design. This increases water extraction demands and places nurseries in competition for water resources with population centers, industry, and other agricultural sectors (Beeson et al., 2004). Since 1992, water applications to container nursery stock in Florida (mean rainfall= 1,100 $mm \cdot y^{-1}$) had been capped at 2,290 $mm \cdot y^{-1}$ until 2003 when this amount was further limited to 1,830 $mm \cdot y^{-1}$ for nurseries in direct competition with municipalities for potable water (Beeson, 2004). Nursery water withdrawal policies are also in place in California, Oregon, North Carolina, and Texas (Beeson et al., 2004).

One method to aid nurseries in conserving water is to schedule irrigation in response to plant water use. Warsaw et al. (2009a) showed that irrigating based on daily water use (DWU) reduced water applications from 6% to 75% compared to a 19 $mm \cdot ha^{-1} \cdot d^{-1}$ control without negatively impacting growth of over 20 ornamental shrubs. From a management perspective, scheduling irrigation based on plant water use is much more practical when the process is automated. Nemali and van Iersel (2006) designed an automated irrigation system that successfully maintained substrate volumetric water content (SVWC) near one of four set points for 43 d. The system produced larger annual bedding plants when grown at a fixed SVWC of 0.22 m^3m^{-3}

compared to 0.32 m^3m^{-3}. Using a similar irrigation system that monitored SVWC using TDR sensors, Cornejo et al. (2005) improved irrigation application efficiency 22% compared to a timer-controlled irrigation system. In order for commercial producers to achieve such efficiency gains, refined automation protocols will be required before widespread adoption of use-based irrigation systems by nurseries is realized.

In addition to concerns about the quantity of water consumed in plant production, effluent leaving nurseries may carry NO_3^--N and PO_4^{3-}-P at concentrations as high as 8 $mg \cdot L^{-1}$ and 5 $mg \cdot L^{-1}$ (Sharma and Bolques, 2007). Although those NO_3^--N levels do not exceed the USEPA safe drinking water threshold (10 $mg \cdot L^{-1}$), the Michigan Department of Environmental Quality (MDEQ) reported that where NO_3^--N is already present, just 0.3 $mg \cdot L^{-1}$ of PO_4^{3-}-P may promote cyanobacteria blooms that can damage sensitive ecosystems (Anonymous, 2008). In addition to regulating concentration, total maximum daily load (TMDL) standards have been developed on a case-specific basis to set a maximum rate at which nutrients can enter a water body (EPA, 2011). The six states in the Chesapeake Bay watershed contribute 60% NO_3^--N and 50% PO_4^{3-}-P in excess of EPA limits to the bay (CBF, 2010). As a result, since 2002 the state of Maryland requires agricultural operations to draft management plans for nitrogen and phosphorus (Lea-Cox et al., 2001). In Florida, agriculture accounts for 98% of all phosphorus imports into the Lake Okeechobee watershed where a phosphorus TMDL of 40 $ug \cdot L^{-1}$ there places agricultural nonpoint sources under intense scrutiny (FDEP, 2001). Nutrient TMDLs have been implemented in Michigan as well for phosphorus levels in 12 watersheds, although few nurseries are affected in this instance (Anonymous, 2011). Research has shown decreased nutrient loading with precision irrigation management (Million et al., 2010; Warsaw et al., 2009b). The former reported reduced total N and P loading into effluent by 19% and 27% compared to a single application of 1 $cm \cdot ha^{-1}$. Similarly, the Warsaw et al. (2009b) system reduced total quantities of NO_3^--N in effluent 38% and 59% in 100% DWU and 75% DWU applications compared to their control.

The objectives of this project were to study the effects of an automated, DWU-based irrigation system on plant performance and runoff water volume and quality. Plant growth index (GI) and dry weight, DWU, water use efficiency (WUE), runoff water volume, and NO_3 and PO_4 concentrations and loads were measured to compare the irrigation system and treatments.

Materials and Methods

Site

The Michigan State University Horticulture Teaching and Research Center (HTRC), Holt, Mich., is located at latitude 42.67 degrees north, longitude -84.48 degrees west, and elevation of 264 m. Plants were grown on 3 x 6 m nursery production beds covered with 6-mil impermeable polypropylene plastic and overlain by permeable landscape fabric. The beds were positioned east to west along the long axis and sloped to the center and westward, thereby channeling runoff water into a collection basin positioned below grade on the west end of each bed. Rectangular basin frames were made of wood and spanned the width of the production beds. An impermeable polypropylene pond liner was inserted and affixed to each frame (see Warsaw et al., 2012 for schematic). Production beds were spaced 3.7 m apart to minimize irrigation drift from neighboring beds. A Michigan Enviro-weather station is located at the HTRC to monitor environmental conditions (MSU, 2011).

Irrigation System

Irrigation was activated in each production bed by a 1.9 cm diameter 24 V alternating current solenoid valve (various manufacturers). Six U8 Series nozzles (Rain Bird Corporation; Azusa, CA) were mounted on 1.3 cm diameter by 0.66 m high risers. The sprinklers were spaced 2.44 m apart along the long edge of each production bed with all water directed inward. Four 90^{o} nozzles were positioned on the corners of the production area, and one- 180^{o} nozzle was positioned between the corner nozzles on each long axis for a total of 6 nozzles per production area, each with a 2.44 m radius of throw to provide 100% nozzle- to-nozzle overlap.

Irrigation system distribution uniformity (DU) and output in each treatment replicate was tested in 2009 using 16 rain gauges randomly interspersed throughout the irrigation zone and allowed to collect water for 20 min. The average application rate was 0.51 $mm \cdot min^{-1}$ (30.6 $mm \cdot hr^{-1}$) with a distribution uniformity of 69.3%. Distribution uniformity and output in each treatment replicate was again tested in 2010. The average application rate was 0.50 $mm \cdot min^{-1}$ (30 $mm \cdot hr^{-1}$) and the DU was 87.8%. The improvement in DU occurred when the system operating pressure was increased in order to maintain a similar application rate compared to 2009.

Plant Material

Rooted cuttings of *Chamaecyparis obtusa* Sieb. and Zucc. 'Filicoides', *Chamaecyparis pisifera* Sieb. and Zucc. 'Sungold', *Thuja occidentalis* L. 'Holmstrup', and *Thuja plicata* Donn 'Zebrina' were obtained from a commercial nursery in 5.7 x 5.7 cm plug containers on 1 August 2008. They were planted in 10.2 L containers with an 85 pine bark : 15 peat moss (vol:vol) substrate between 2 – 9 Sept. 2008. All cultural practices except irrigation were identical for all treatments. On 22 June 2009 and 6 June 2010, 54 g of 19-2.6-10 (%N-P-K) fertilizer with micronutrients and Polyon® Reactive Layers Coating controlled release technology (Harrell's Inc., Lakeland, FL) was topdressed to each container. Total quantities of NO_3^--N and PO_4^{3-}-P applied in both 2009 and 2010 were equivalent to 285 $kg \cdot ha^{-1}$ and 39 $kg \cdot ha^{-1}$, assuming identical container spacing to this study and 100% land utilization. Predicted release duration at substrate temperatures of 21.1^o C and 26.7^o C ranged from 6 to 5 months. Weeds were removed by hand pulling as necessary. Plants were overwintered from 2009 to 2010 in a minimally-heated (-2.2^o C) quonset house covered with 4 mil overwintering film permitting 30% light transmission. After over-wintering, plants were placed on the production beds in their original configuration on 11 May 2010.

Experimental Design

Four irrigation treatments were replicated three times and randomly assigned to 12 production beds in a completely randomized design. The treatments were: 1) control application of 19 $mm \cdot ha^{-1} \cdot d^{-1}$, 2) irrigation applied to replace 100% daily water use (100DWU), 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle (100-75), and 4) a 3-day application cycle replacing 100% DWU on the first day and 75% DWU on the second and third days (100-75-75). Each treatment replicate contained six subreplicates of each of the four species for a total of 24 experimental plants in each production bed. Experimental plants were randomized in three rows of eight at the center of the production bed with guard plants surrounding the perimeter to reduce edge effects. Guard plants consisted of many species having similar growth rates to the experimental plants and were arranged in the same sequence in each treatment replicate. Guard plants were assigned a position in each treatment replicate in 2009 and were placed in the same position in 2010. Irrigation treatments were applied approximately every 24 h beginning at 0700 HR from 23 June 2009 to 16 October 2009 (treatment duration = 114 d) and 7 June 2010 to 31 October 2010 (treatment duration = 147 d). In both seasons and within each treatment, DWU irrigation applications were always made based on the species with the highest DWU within each treatment. In the cool months between growing seasons, all plants were uniformly irrigated to container capacity via an overhead system as necessary.

Daily Water Use and Irrigation Scheduling, 2009

Substrate volumetric water content (SVWC) was measured in 2009 for every plant using a ThetaProbe Type ML2x TDR soil moisture sensor (Delta-T Devices Ltd., Cambridge, U.K.) read with a ThetaMeter Hand-Held Readout Unit Type HH1 (Delta-T Devices Ltd.). At initiation of the study, irrigation was applied until the substrate for all plants exceeded container capacity. Gravimetric water was allowed to drain for 30 min. Then an initial SVWC measurement was taken for each plant, and a final measurement was taken after 24 h. The Theta probe was inserted vertically into the substrate to a depth of 6 cm in three locations 120^{o} apart halfway between the center and the outer edge of the container. The measurements were converted to SVMC using a substrate-specific equation developed by Warsaw et al. (2009a) for the same substrate. The SVWC differential was multiplied by the average container substrate volume (9.7 L·container^{-1}) to determine daily water use (DWU). Control and DWU-based treatments were programmed into a Rain Bird ESP-12LX Plus controller (Rain Bird Corporation; Azusa, CA). Irrigation began at 0700 HR daily. New DWU were obtained approximately every 21 d, and irrigation was adjusted accordingly.

Daily Water Use and Irrigation Scheduling, 2010

In 2010, 10HS time capacitance soil moisture sensors (Decagon Devices, Inc.; Pullman, WA) replaced the ThetaProbe to provide continuous real-time SVWC sampling and irrigation control. A total of 48 sensors, one per species in each replicate, were connected in single-ended configuration to an AM16/32B multiplexer (Campbell Scientific, Inc.; Logan, UT), which was operated by a CR1000 micrologger (Campbell

Scientific, Inc.). An SDM-CD16AC relay controller (Campbell Scientific, Inc.) connected to the micrologger controlled the irrigation solenoid valves located at each treatment replicate. The 24 V alternating current power required by the solenoid valves was provided via a common wire from the "Master Valve" terminal on an ICC-800PL irrigation controller (Hunter Industries, Inc., San Marcos, CA) to each relay on the controller.

The micrologger recorded SVWC for each probe at 15 min intervals from 7 June to 31 October 2010. Between 7 June and 19 June, several out-of-range SVWC readings occurred, mostly from the same sensors. To correct for this, each of the 48 sensors was individually calibrated to the substrate *in situ* from 19 June to 20 June. Irrigation was applied to bring the substrate to container capacity, and each container was weighed after drainage ceased using a PM 30 electric balance (Mettler-Toledo, Inc.; Columbus, OH). Five subsequent weights were taken during the 24 hour dry-down period and recorded with coinciding sensor output. These data were plotted using Microsoft Excel (2007) and the trend line feature was used to obtain a single best-fit quadratic equation. Calibrations were verified using the PROC REG function in SAS (SAS Institute; Cary NC) before inclusion in the CR1000 program. The calibration equations were then incorporated in the CR1000 programming using Version 2.7.0.16 of CRBasic Editor (Campbell Scientific, Inc.; 2006).

From 7 June to 31 October, DWU was calculated as:

$$DWU = SVWC_{initial} - SVWC_{final}$$

where: $SVWC_{initial}$ = SVWC one hour after irrigation

$SVWC_{final}$ = SVWC immediately before next irrigation cycle

The micrologger program began the irrigation regimen each day at 0700 HR. Beginning June 6, with no initial SVWC to reference from previous days, substrate moisture had to be raised to container capacity before recording the first initial SVWC. From 2000 HR on 5 June to 0600 HR on 6 June, 31.23 mm of steady rainfall occurred, which added 1.75 L to each container. This was considered sufficient to bring the substrate to container capacity for the calculation of DWU on Day 1 of the experiment. The program determined the highest DWU in the treatment replicate, which was then multiplied by the irrigation system application rate to determine a run time in seconds. Last, the appropriate treatment proportion of 100% or 75% was then multiplied by the run time before activating the relay controller for the necessary duration. The initial SVWC measurement for calculation of DWU for the following day was logged 1 h after irrigation termination to allow for gravimetric water drainage. The following day just before initiating irrigation in each zone, final SVWC was logged and the new DWU calculation made. The micrologger repeated this process in all treatment replicates each day for the duration of the study.

Plant Performance

Comparisons of DWU between different species grown over the two seasons were made to standardize for environmental conditions by comparing crop coefficients (K_C), which were determined using the formula $K_C = ET_A / ET_0$ (Allen et al., 1998). These calculations were made for each taxon in both 2009 and 2010 using data obtained from the on-site weather station (www.enviroweather.msu.edu). Plants were classified in this study as low ($K_C < 2$), moderate ($2 \leq K_C < 3$), or heavy ($K_C \geq 3$) water users as described by Warsaw et al. (2009a).

Monthly growth index (GI) was calculated to assess plant performance under the four irrigation treatments. Plant height (H) measurements were taken from the container rim. Plant widths were measured along the north – south (W_{NS}) and the east – west axis (W_{EW}) axis, and GI was calculated as $[(H + W_{NS} + W_{EW}) / 3]$. A permanently affixed container label was used to maintain orientation of the plants. For one species, plant shoot dry weight was measured using three *C. obtusa* 'Filicoides' taken from each treatment replicate. The stem was cut at the substrate surface, and the entire top was bagged, oven dried, and weighed.

Runoff Collection and Analysis

Runoff water from the production beds was collected for two consecutive days each month. Effluent collection occurred on a day when treatments received 100% DWU and another day when 75% DWU was applied. Water was allowed to drain off the production beds for 0.5 h after irrigation. A small pump and vacuum were used to transfer water from the collection basin into a container to measure volume of total effluent recovered. Water samples were obtained from each treatment replicate to measure NO_3^--N and PO_4^{3-}-P concentrations in runoff water. Samples were maintained at 3^o C until being submitted to the Michigan State University Soil Testing Laboratory for NO_3^--N and PO_4^{3-}-P analysis. The cadmium reduction method was used for NO_3^--N analysis and the Bray and Kurtz P-1 Test for PO_4^{3-}-P analysis (Frank et al., 1998). To determine net nutrient load, bulk quantities of nutrients in the effluent were calculated by multiplying nutrient concentrations by the volume of effluent collected and are expressed as $g \cdot ha^{-1} d^{-1}$. The proportion of NO3-N and PO4-P recovered were calculated as the ratio of nutrient quantities recovered : applied.

Statistical analysis

Data for each species were analyzed individually for irrigation volume, DWU, K_C, GI, GII, WUE, WUE_p, dry weight, effluent recovery volume, nutrient concentration, nutrient load, and percent nutrient recovery. Data were found to be normal using the PROC UNIVARIATE procedure in SAS (SAS Version 9.1; SAS Institute, Cary, NC). Data was tested with analysis of variance using the PROC GLM procedure of SAS. When significant ($\alpha = 0.05$), Tukey's Honestly Significant test was used to separate means.

Results and Discussion

Irrigation Volume

Cumulative and average daily ET_0 for the 2009 treatment period equaled 369 mm and 3.15 mm and in 2010 were 491 mm and 3.34 mm. A total of 226 mm and 275 mm of rainfall (Figure 2.1) occurred during the 2009 and 2010 treatment periods contributing 13 $L \cdot container^{-1}$ and 16 $L \cdot container^{-1}$. In 2009, irrigation was not applied on three days when rainfall events exceeded 19 mm. Between the time the plants were

Table 2.1. Daily irrigation application (L·container^{-1}·d^{-1}) (± SE) and total irrigation applied (L·container^{-1}) to 4 irrigation treatments from 25 June through 16 October 2009 and 7 June through 31 October 2010.

Treatment	Irrigation application (L·container^{-1}·d^{-1})	Total irrigation applied (L·container^{-1})
2009		
Control[z]	1.07 ± 0.00[y] A	116.96 A
100DWU	0.80 ± 0.02 B	91.29 B
100-75	0.70 ± 0.03 C	79.46 C
100-75-75	0.67 ± 0.03 D	75.81 D
2010		
Control	1.07 ± 0.00 A	157.29 A
100DWU	0.84 ± 0.02 B	124.89 A
100-75	0.91 ± 0.03 B	135.11 A
100-75-75	0.85 ± 0.03 B	125.55 A

[z]Control = 19 mm·application^{-1} (1.07 L·container^{-1}·day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle 100% DWU replacement the first day then 2 days 75% DWU replacement. Irrigation scheduling based on: 2009) highest DWU of the 4 taxa recorded on each day of sampling; 2010) highest DWU of the 4 taxa in each treatment replicate each day.

[y]Means separation performed with Tukey's Test (α = 0.05), n = 115 d (2009) and n = 147 d (2010). Means followed by the same letter(s) are not different.

moved outdoors on 11 May 2010 and the beginning of treatments on 7 June, 10 mm of irrigation was applied daily to all treatments. An additional 133 mm of precipitation fell during this period for a total of 403 mm of water received by all treatments. During the treatment period, total irrigation applied to the control was 2166 mm (117 $L{\cdot}container^{-1}$; Table 2.1) in 2009 and 2795 mm (157 $L{\cdot}container^{-1}$) in 2010. Compared to the control, daily irrigation applications to the 100DWU, 100-75, and 100-75-75 treatments were reduced by 22%, 32%, and 35% in 2009 and 22%, 15%, and 21% in 2010, respectively (Table 2.1). Across each two or three-day cycle, irrigation applications in the 100-75 and 100-75-75 treatments were 87.5% and 83.33% of DWU.

In 2009, seasonal DWU of *T. plicata* 'Zebrina' and *C. obtusa* 'Filicoides' in the 100-75-75 treatment was 0.849 $L{\cdot}container^{-1}{\cdot}d^{-1}$ and 0.889 $L{\cdot}container^{-1}{\cdot}d^{-1}$, both higher than respective control plants at 0.644 $L{\cdot}container^{-1}{\cdot}d^{-1}$ and 0.675 $L{\cdot}container^{-1}{\cdot}d^{-1}$. In addition, *C. pisifera* 'Sungold' in the 100-75-75 treatment exhibited higher DWU at 0.859 $L{\cdot}container^{-1}{\cdot}d^{-1}$ than in the 100-75 treatment of 0.700 $L{\cdot}container^{-1}{\cdot}d^{-1}$. In 2010, DWU of *C. obtusa* 'Filicoides' in the 100-75 and 100-75-75 treatments was 0.675 $L{\cdot}container^{-1}{\cdot}d^{-1}$ and 0.643 $L{\cdot}container^{-1}{\cdot}d^{-1}$, both higher than the 100DWU of 0.619 $L{\cdot}container^{-1}{\cdot}d^{-1}$. Similarly, *T. occidentalis* 'Holmstrup' had higher DWU in the 100-75-75 treatment at 0.622 $L{\cdot}container^{-1}{\cdot}d^{-1}$ than either the 100DWU (0.381 $L{\cdot}container^{-1}{\cdot}d^{-1}$) or control treatments (0.533 $L{\cdot}container^{-1}{\cdot}d^{-1}$).

Figure 2.1. Daily (bars) and cumulative (line) precipitation from 25 June to 16 October (Day 114) 2009 and 7 June (day 348) to 31 October 2010 (Day 494). Data obtained from the Enviro-weather Automated Weather Station Network.

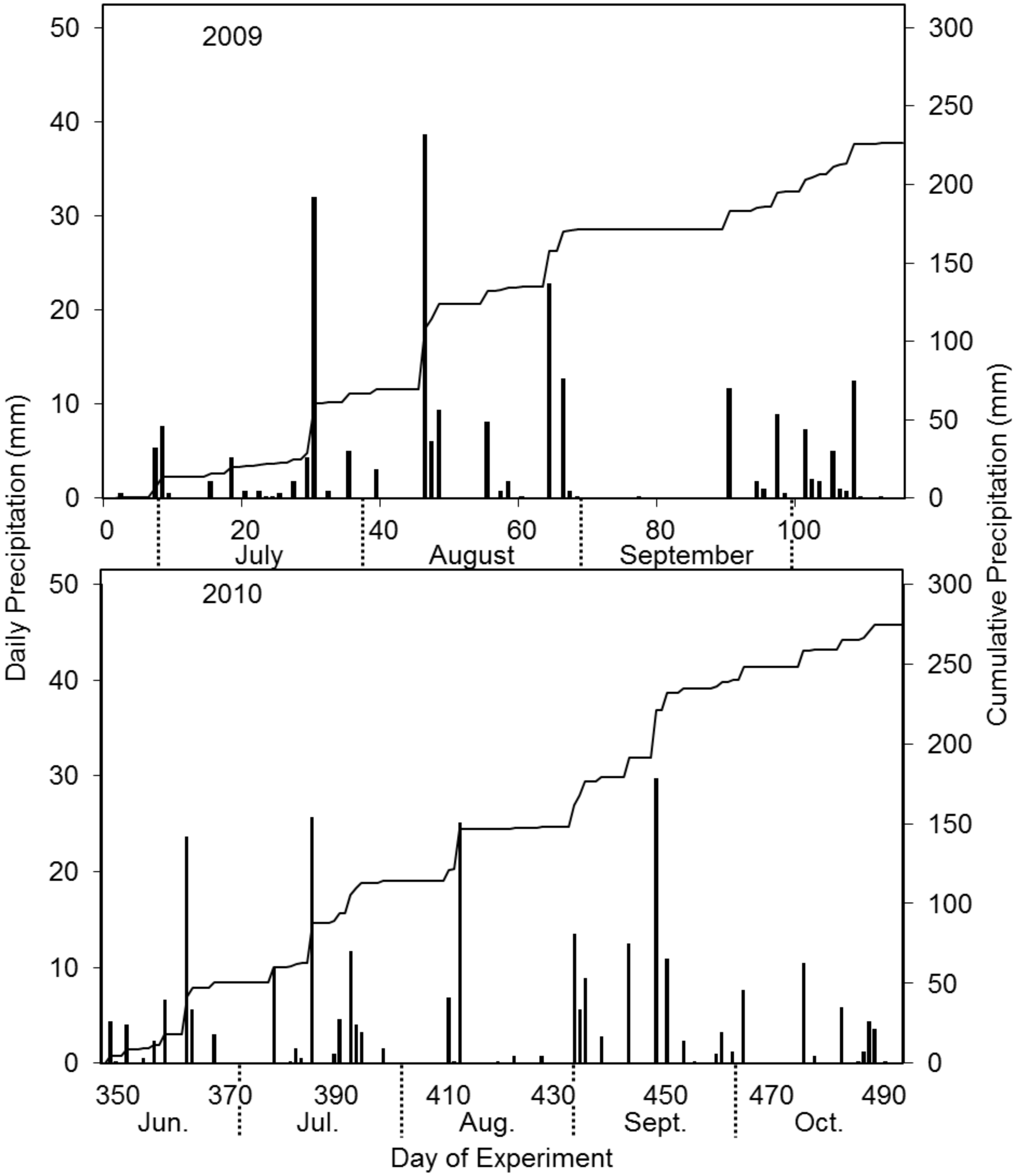
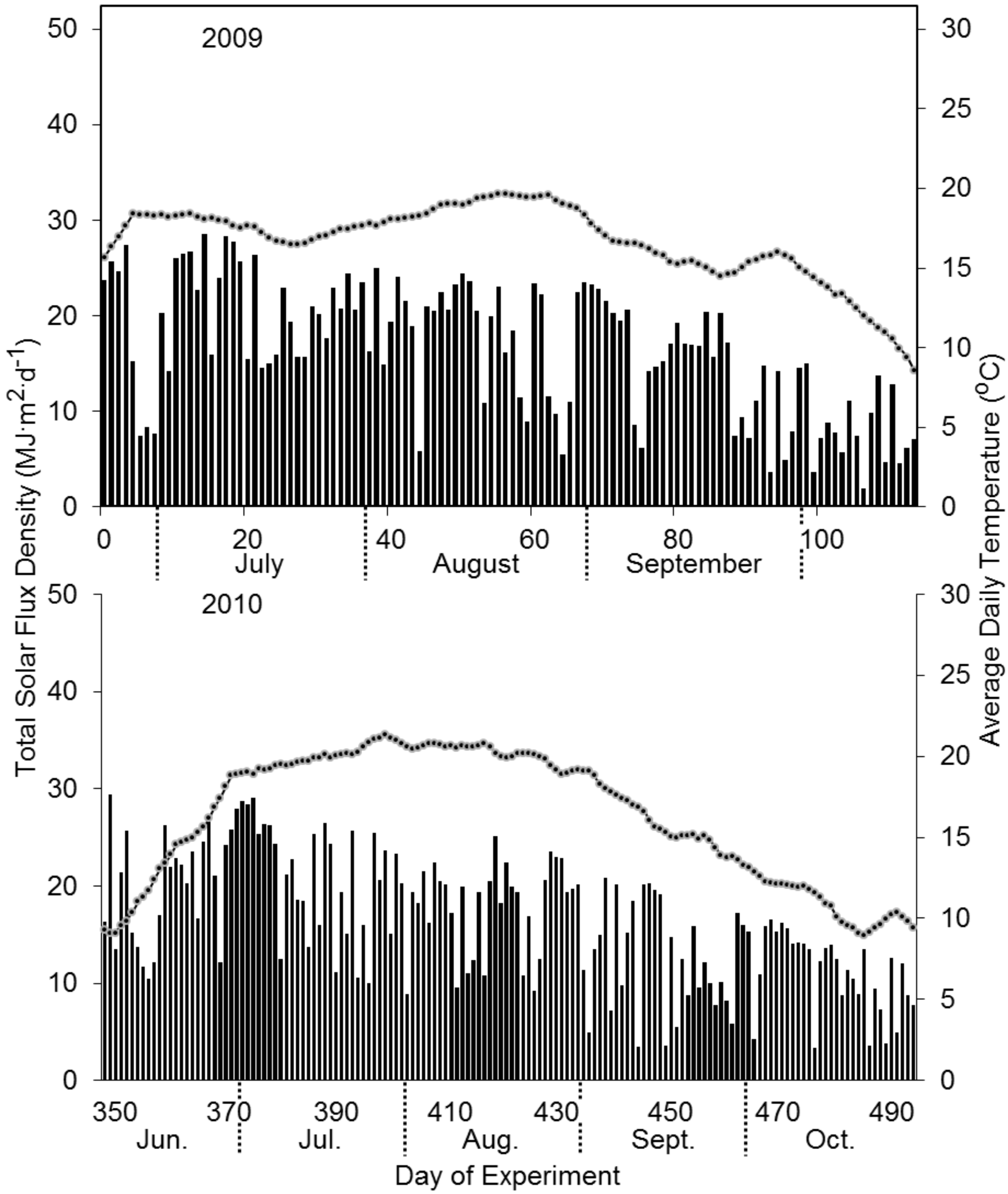


Figure 2.2. Daily total solar flux density (bars) and daily average temperature (line) from 25 June to 16 October (Day 114) 2009 and 7 June (day 348) to 31 October 2010 (Day 494). Data obtained from the Enviro-weather Automated Weather Station Network.



Daily fluctuations in DWU very closely tracked fluctuations in ET_0 (Figure 2.3). Maximum DWU in 2009 occurred on day 78 (10 Sep.). In the first half of 2010, DWU was generally higher before showing a marked decline in early September (Figure 2.3). This decline corresponded to increasing frequency of precipitation (Figure 2.1) and decreasing temperatures and solar flux (Figure 2.2). Maximum DWU occurred on different days for each species, with the highest recorded DWU of all taxa occurring in *Chamaecyparis obtusa* 'Filicoides' on day 399 (28 July 2010). Moreover, DWU only exceeded the control on three days in 2010, and in only two of the four taxa (Figure 2.3). Precipitation resulted in calculation of a negative DWU on 10 days throughout 2010 when irrigation was not applied. DWU only exceeded control irrigation applications on four days for *C. obtusa* 'Filicoides', three days for *T. plicata* 'Zebrina', two for *T. occidentalis* 'Holmstrup', and one day for *C. pisifera* 'Sungold'. Consequently, irrigation was applied to the control in excess of plant needs on the majority of days throughout this study, particularly later in the season as temperatures fell and precipitation was frequent.

Under the classification system adopted from Warsaw et al. (2009a), all taxa in 2009 were high water users and most were high users in 2010 (K_C>3; Table 2.2). However, seasonal K_C of *T. plicata* 'Zebrina' in 2010 was <3 for all but the 100 DWU treatment, which classifies it in the remaining treatments as a moderate water user. Among all taxa, *T. plicata* 'Zebrina' had both the lowest crop coefficient at 2.1 in the 2010 season from the 100-75 treatment and the highest at 5.8 in the 100-75-75

Figure 2.3. Daily Water Use (DWU) from 25 June to 16 October 2009 and 7 June to 31 October 2010 of A) *Chamaecyparis obtusa* ‘Filicoides’, B) *Chamaecyparis pisifera* ‘Sungold’, C) *Thuja occidentalis* ‘Holmstrup’, and D) *Thuja plicata* ‘Zebrina’ grown in 10.2 L containers.

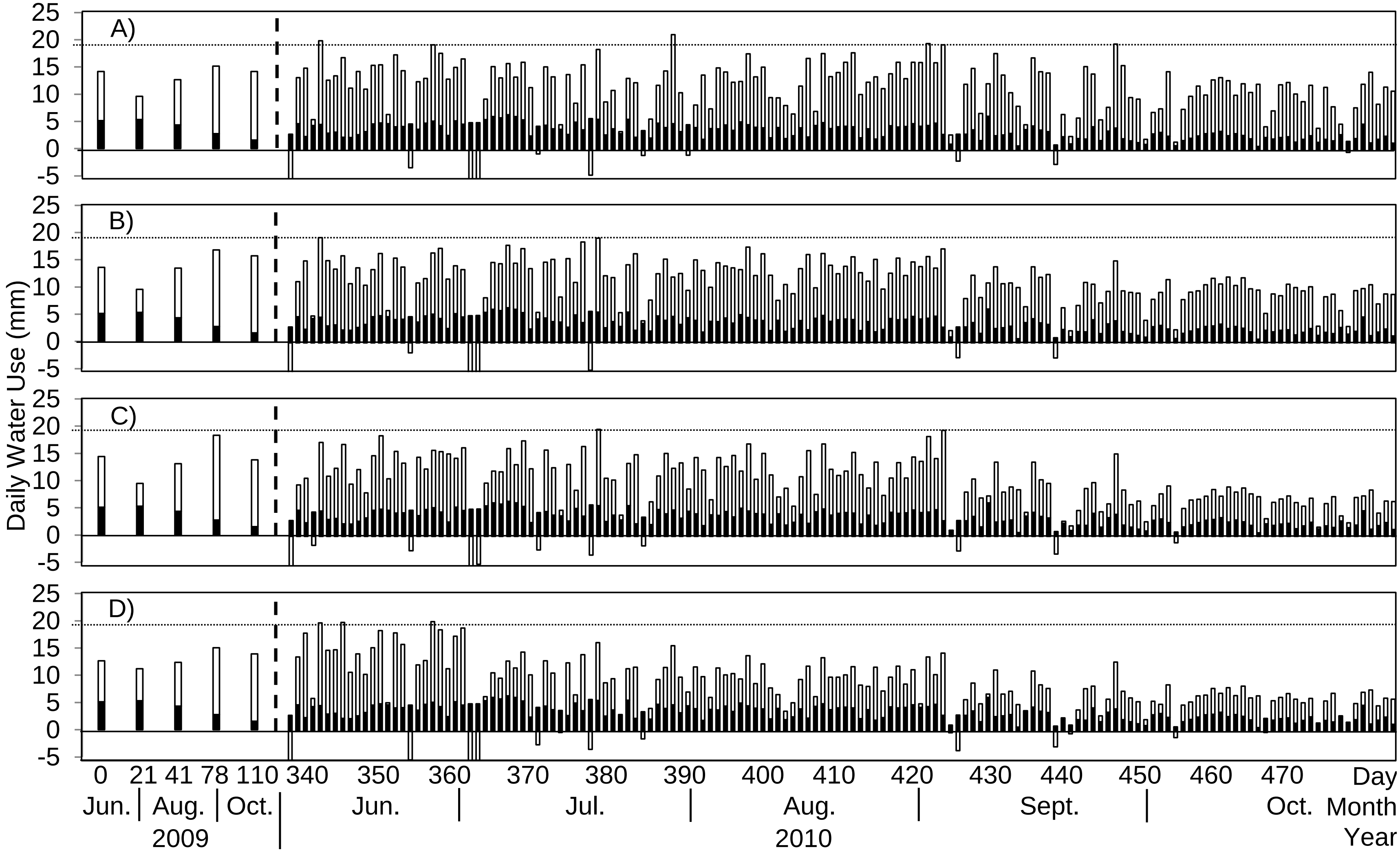


Figure 2.3 (cont'd)

The shaded portions of bars represent daily ET_0 from 25 June to 16 October 2009 and 7 June to 31 October 2010. White portions of each bar represent DWU. Negative values indicate precipitation in excess of DWU. Dotted horizontal line indicates control treatment of 19mm·application^{-1}. Dashed vertical line separates 2009 and 2010 seasons. Daily ET_0 values obtained from the Enviro-weather Automated Weather Station Network.

treatment for 2009 (Table 2.2). When comparing treatments in 2010, *C. obtusa* 'Filicoides' and *T. occidentalis* 'Holmstrup' both had K_C <3 in the 100DWU treatment making them moderate water users in that treatment only. For the other taxa, lowest K_C occurred in the 100-75 or 100-75-75 treatments, also making these moderate users. Using the same classification methods as the current study, *Thuja plicata* Donn 'Atrovirens' was rated a low user in Michigan in 2006 with a K_C of 1.7, and *T. occidentalis* L. 'Techny' grown in 2007 was rated a moderate user with a K_C of 2.6 (Warsaw et al., 2009a). Overall K_C in flowering shrubs reached as high as 6.8 (Warsaw et al., 2009a). Others reported maximum K_C = 4.7 (Schuch and Burger, 1997) and 5.1 (Burger et al., 1987). From the DWU data obtained using the capacitance sensors in the current study, Figure 3 also illustrates the day-to-day fluctuations in the 2010 K_C, expressed as DWU:ET_0. Calculation of K_C at this resolution requires sensor monitoring, which is not widely adopted by nurseries at this time. For more immediate implementation, Schuch and Burger (1997) presented an approach involving the

Table 2.2. Seasonal crop coefficients ($L \cdot container^{-1} \cdot d^{-1}$) of four conifers grown in 10.2 L containers under four irrigation treatments administered 25 June through 16 October 2009 and 7 June through 31 October 2010. Seasonal K_C calculated as DWU:ET_0.

Taxa	Crop Coefficient			
2009	Control[z]	100DWU	100-75	100-75-75
Chamaecyparis obtusa 'Filicoides'	3.41 Ba[y]	4.46 ABa	4.16 ABa	5.36 Aa
Chamaecyparis pisifera 'Sungold'	4.53 Aa	4.73 Aa	4.10 Aa	5.65 Aa
Thuja occidentalis 'Holmstrup'	4.39 Aa	4.19 Aa	4.68 Aa	5.32 Aa
Thuja plicata 'Zebrina'	3.74 Ba	3.99 Ba	4.05 Ba	5.79 Aa
2010				
Chamaecyparis obtusa 'Filicoides'	3.84 Aa[x]	2.86 Bc	4.15 Aa	3.95 Aa
Chamaecyparis pisifera 'Sungold'	3.70 Aab	4.15 Aa	4.27 Aa	2.46 Bb
Thuja occidentalis 'Holmstrup'	3.20 Ab	2.11 Bd	3.31 Ab	3.57 Aa
Thuja plicata 'Zebrina'	2.27 Cc	3.43 Ab	2.10 Cc	2.81 Bb

[z]Control = 19 $mm \cdot application^{-1}$ (1.07 $L \cdot day^{-1}$); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Irrigation scheduling based on: 2009) highest DWU of the 4 taxa recorded on each day of sampling; 2010) highest DWU of the 4 taxa in each treatment replicate each day.

[y]Separation of means performed with Tukey's Test ($\alpha = 0.05$), 2009 n = 18, 2010 n = 3. Means followed by the same letters (capital letters in rows, lower case letters in columns) are not different within respective years.

reassessment of K_C every few weeks. Additionally, Niu et al. (2006) showed that K_C differed by calendar month for container-grown shrubs in Texas. Such intervals are similar to those between DWU measurements made in 2009 from the current study. At the very least, K_C are likely best reassessed seasonally with changing weather patterns since K_C made a few abrupt transitions, particularly with the marked decrease in early September of 2010 (Figure 2.3).

Plant Response to Irrigation Treatments

Growth index did not differ among any taxa in 2009 (Figure 2.4). In 2010, GI for *C. obtusa* 'Filicoides' in the 100DWU treatment was larger than the control plants on all sampling dates. In 2010, *C. obtusa* 'Filicoides' also had a higher GII in the 100DWU treatment than the control (Table 2.3). During the treatment period, *T. plicata* 'Zebrina' grew more than any taxa in the DWU treatments (9.7 cm, 8.8 cm, and 8.6 cm in the 100DWU, 100-75, and 100-75-75 treatments, respectively). An exception was that *T. plicata* 'Zebrina' in the 100DWU treatment did not differ from *T. occidentalis* 'Holmstrup'. Similar to GI, shoot dry weight of *C. obtusa* 'Filicoides' was 163.6 g in the 100DWU treatment and 134.9 g in the 100-75-75 treatment, both higher than the control of 51.7 g. It is noteworthy that while the DWU treatments received less water than the control, growth was not lower for any taxa at the conclusion of the study.

The ability to successfully produce plants under water conserving irrigation regimes without impacting growth has been documented in several cases. In a deficit

Figure 2.4. Growth index of a) *Chamaecyparis obtusa* 'Filicoides', b) *Chamaecyparis pisifera* 'Sungold', c) *Thuja occidentalis* 'Holmstrup', and d) *Thuja plicata* 'Zebrina' grown in 10.2 L containers and subjected to 4 irrigation treatments from 25 June (Day 0) to 16 October 2009 and 7 June (Day 348) to 31 October 2010. Control = 19 mm·application^{-1}; 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Irrigation scheduling based on: 2009) highest DWU of the 4 taxa recorded on each day of sampling; 2010) highest DWU of the 4 taxa in each treatment replicate each day. Dashed vertical line separates 2009 and 2010 seasons. Each day was analyzed separately (Tukey's test, α = 0.05). Means followed by the same letters are not different. ns = not significant. n=18.

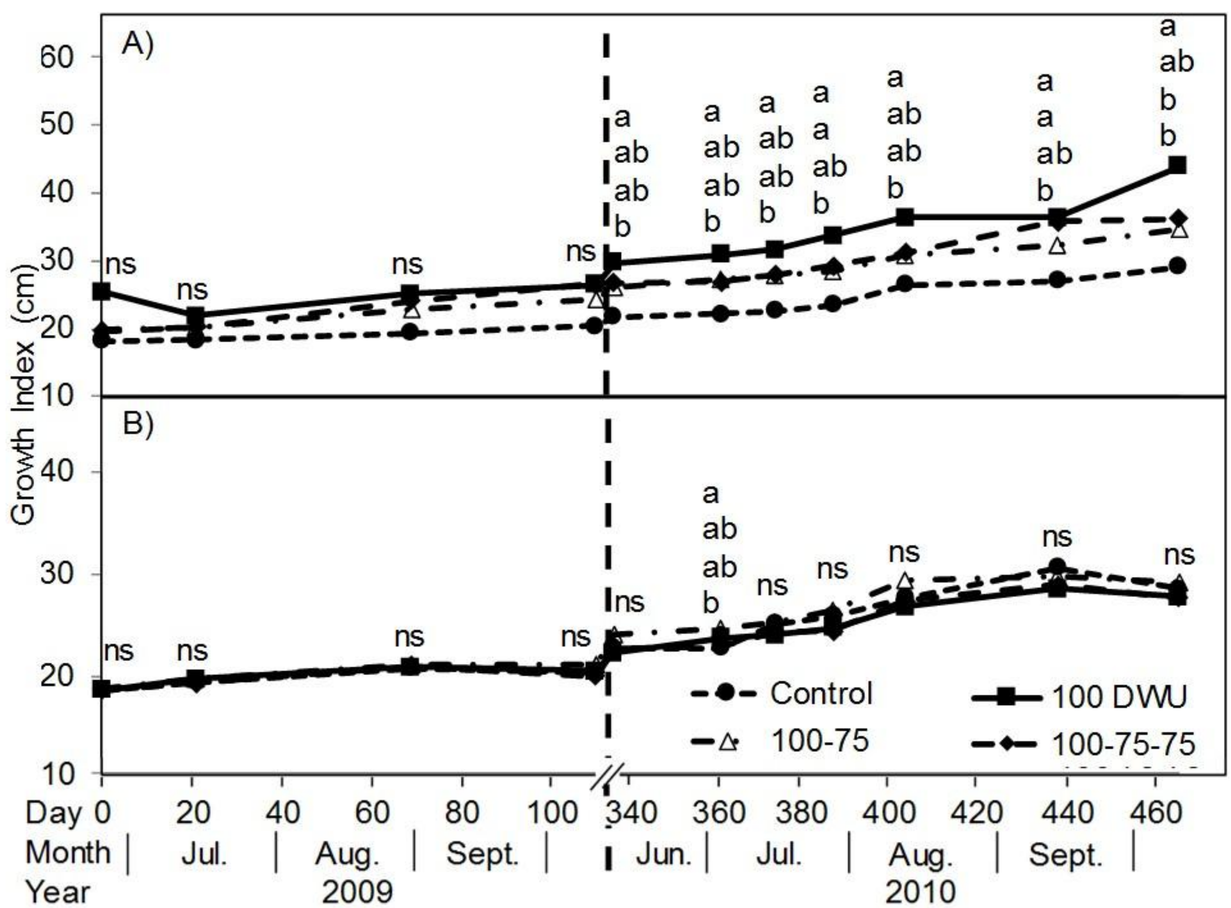
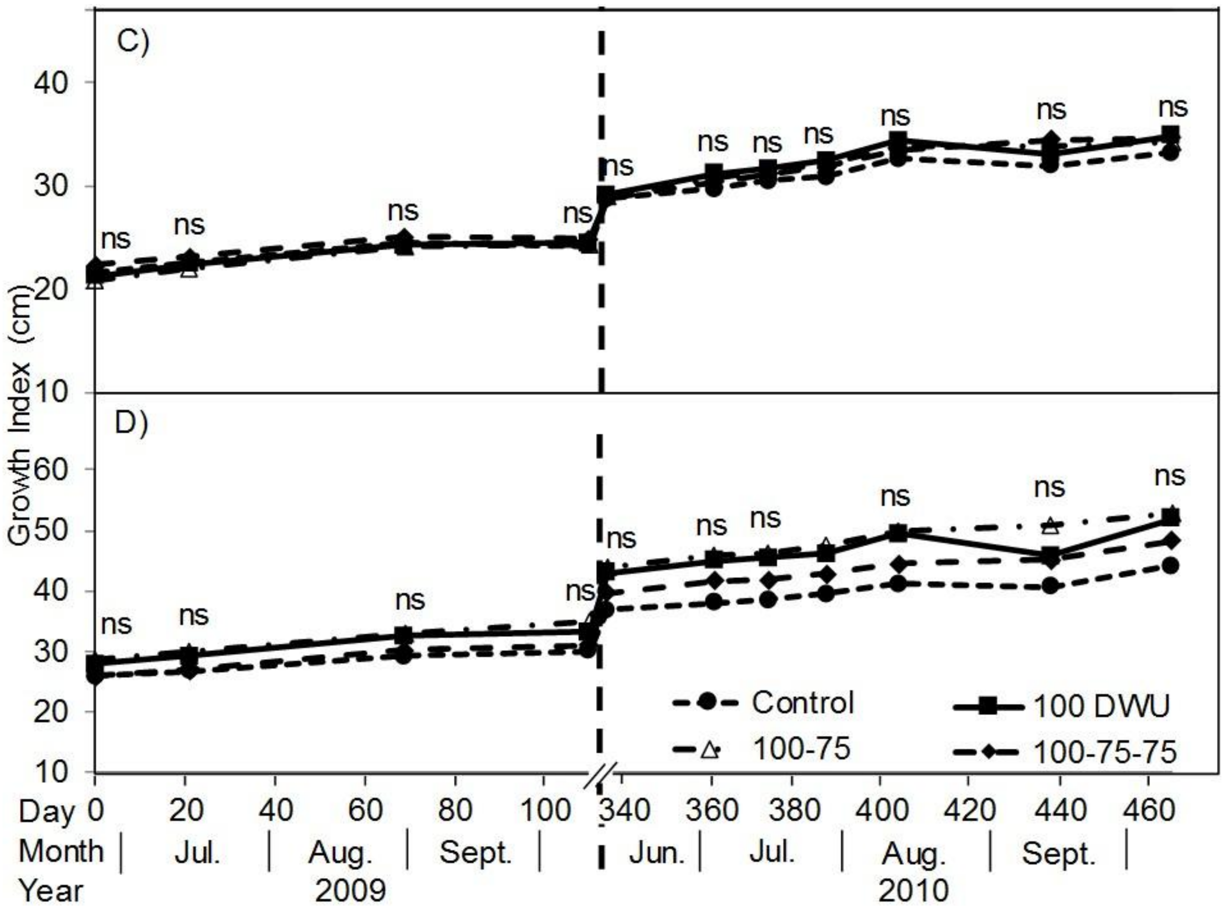


Figure 2.4 (cont'd)



irrigation study, 90% of shoot growth could still be produced at irrigation volumes of 1.0x available water compared to 1.5x available water, a ≈40% reduction in irrigation volume (Groves et al., 1998). Similarly, a low LF of 0.0 to 0.2 conserved 44% of irrigation water versus a LF of 0.4 to 0.6, although the former resulted in an 8% reduction in total plant dry weight (Tyler et al., 1996). In both studies, precise irrigation applications saved water, yet growth was not seriously affected. In the current study, plants in the 100-75-75 treatment incurred minor substrate moisture deficits during two-thirds of the study yet there were no cases of reduced growth from this treatment in any of the four taxa.

Table 2.3. Growth index increase (GII) (cm) of 4 conifers subjected to 4 irrigation treatments between 16 October 2009 to 7 June 2010.

Taxa	Treatment			
2009	Control[z]	100DWU	100-75	100-75-75
GII				
C. o. 'Filicoides'	1.45 B[y]b[x]	5.22 ABa	4.48 ABab	7.69 Aa
C. p. 'Sungold'	1.70 Aab	1.89 Ab	2.37 Ab	1.39 Ac
T. o. 'Holmstrup'	2.63 Aab	3.26 Aab	3.57 Ab	2.49 Ac
T. p. 'Zebrina'	4.22 Aa	5.30 Aa	6.43 Aa	5.04 Ab
2010				
GII				
C. o. 'Filicoides'	7.50 Ba	12.71 Aa	9.50 ABa	9.32 ABa
C. p. 'Sungold'	4.78 Aa	4.96 Ac	5.04 Ab	5.09 Ac
T. o. 'Holmstrup'	4.48 Aa	5.76 Abc	5.31 Ab	5.90 Abc
T. p. 'Zebrina'	7.28 Aa	8.92 Ab	9.02 Aa	8.64 Aa

[z]Control = 19 mm·application^{-1} (1.07 L·day^{-1}); 100DWU = 100% daily water use (DWU) replacement each day; 100-75 = 2 day cycle alternating 100% DWU and 75% DWU; and 100-75-75 = 3 day cycle with 100% DWU replacement the first day then 2 days 75% DWU replacement. Irrigation scheduling based on highest DWU of the 4 taxa recorded on each day of sampling.

[y]Comparisons between means in each row are marked with capital letters. Means of the same letters are not different; Tukey's Test (α = 0.05), 2009: n = 18, 2010: n=3.

[x]Comparisons between means in each column are marked with lowercase letters. Means of the same letters are not different; Tukey's Test (α = 0.05), 2009: n = 18, 2010: n=3.

Warsaw et al. (2009a) reported that whenever plants in DWU treatments were larger than control plants, they had received less water than those in the control. However, the majority of plants studied (20 of 24) were unaffected by irrigation treatment (Warsaw et al., 2009a), as was the case in the current study; only one of four species was affected by treatment.

Other authors have provided a rationale for similar differences in growth that also may explain the growth differences that were observed for *C. obtusa* 'Filicoides'. Since control irrigations were generally above DWU, some of the nutrients supplied by the slow-release fertilizer may have been lost from the substrate due to higher leaching compared to DWU treatments. In their two-year study, Warsaw et al. (2009b) explained that leaching in the control was the probable cause for three of their four species in DWU-based treatments being larger than their control (also 19 $mm \cdot ha^{-1} \cdot application^{-1}$).

Runoff Volume

Runoff volumes from the DWU treatments were lower than the control on all measurement days except day 3 (Figure 2.5). Both *C. obtusa* 'Filicoides' and *T. plicata* 'Zebrina' showed higher DWU in the 100-75-75 treatment than the control, which means that prior to irrigation, SVWC in the 100-75-75 treatment was frequently lower than the control. Watering to a deficit likely contributed to reduced effluent recovery in the 100-75-75 treatment following irrigation applications. Additionally, higher irrigation rates of the control and the 100% application rate led to higher volumes of water being applied off target, which increased total effluent. Highest volumes of irrigation and effluent recovered occurred on day 81 for the 75% DWU applications, day 82 for the 100% applications, and highest effluent volume recovery for the control occurred on day 82. The lowest volumes applied and recovered for these rates occurred on day 39. The 100% and 75% DWU irrigation volumes overall were 34% and 51% less than the control. Of the volume applied, 49%, 46% and 39% was recovered as effluent in the control, 100% DWU and 75% DWU applications, respectively. Warsaw et al. (2009b)

Figure 2.5. Applied irrigation and recovered runoff from 3m x 6m production areas (projected to L ha^{-1}) from 25 June (day 0) to 16 October 2009 and 7 June (day 348) to 31 October 2010 (day 494) for 4 conifers growing in 10.2 L containers.

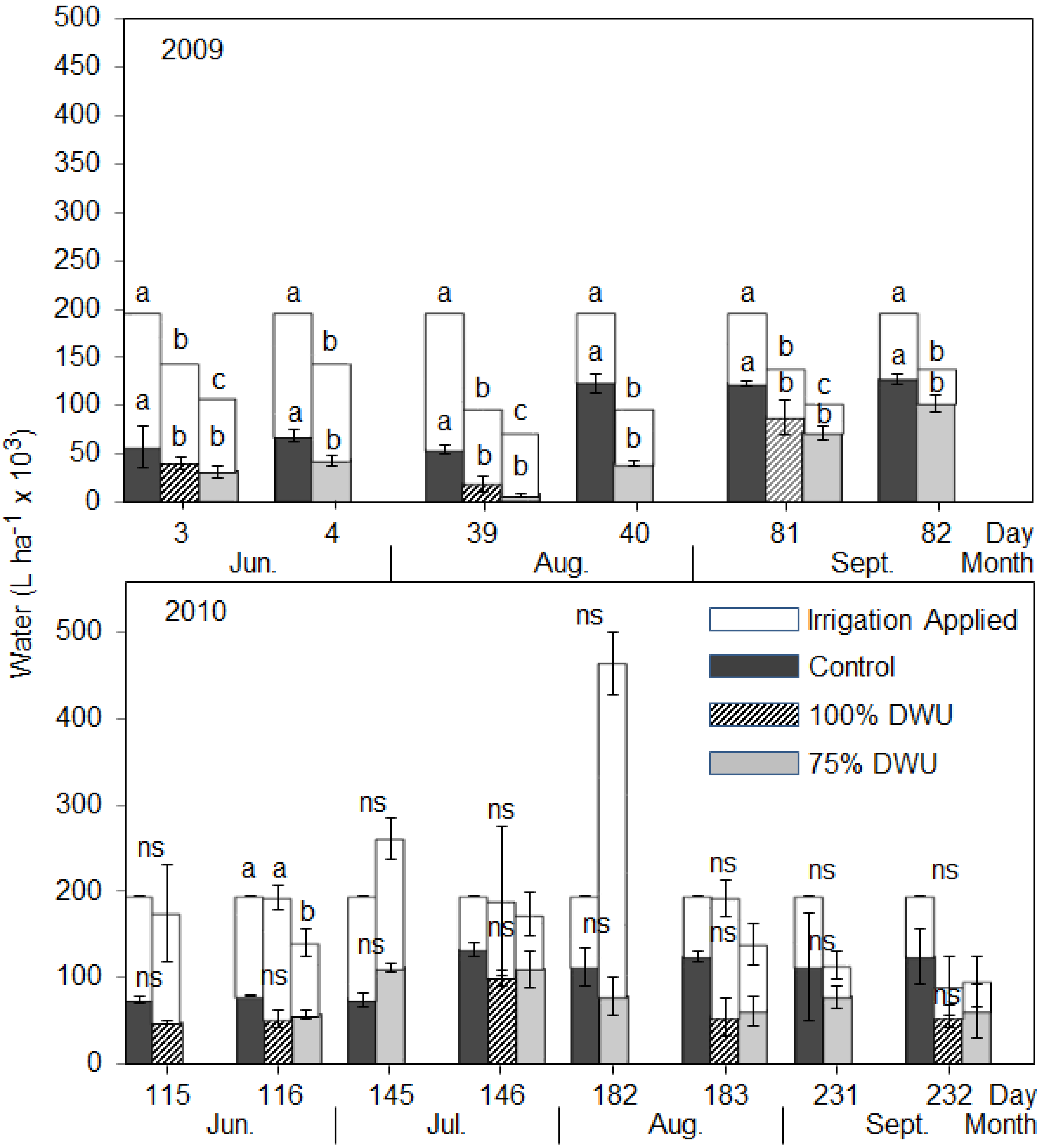


Figure 2.5 (cont'd)
On days with 2 bars, all DWU treatments received irrigation at 100% DWU replacement. On days with 3 bars, 100-75 and 100-75-75 treatments were scheduled at 75% DWU replacement. Control treatment equivalent of 190 x 10^3 $L{\cdot}ha^{-1}$ applied daily. Means separation for each day performed using Tukey's Test (α = 0.05, ns= not significant, n=3).

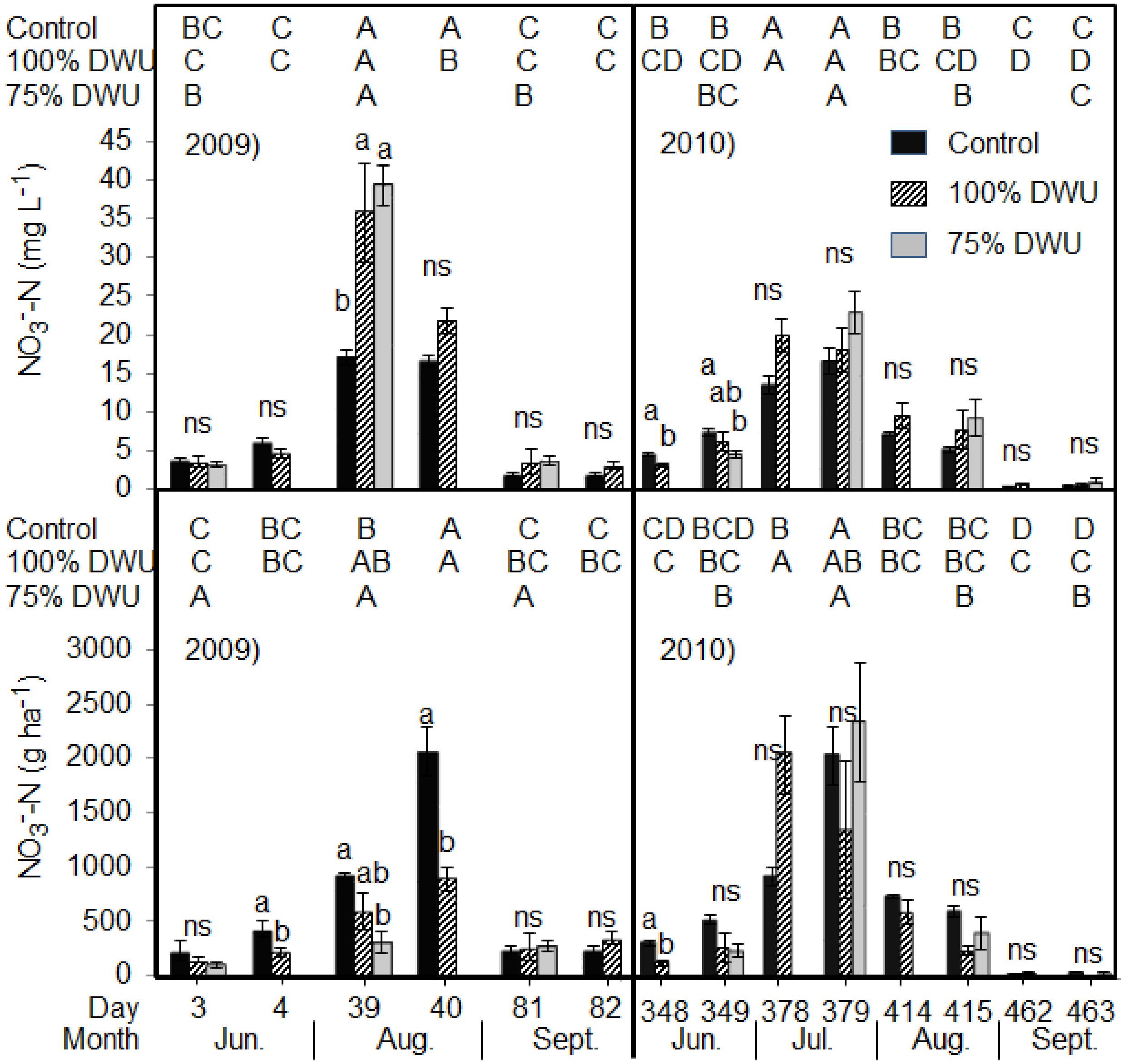
reported similar results with 60%, 37%, and 32% effluent being recovered after their control, 100% DWU, and 75% DWU irrigation applications. Similarly, studies by Fare et al. (1994) and Karam and Niemiera (1994) demonstrated that reduced irrigation volumes in turn reduced leaching.

In contrast to 2009, irrigation application rates in 2010 were not consistent between runoff collection days since DWU was determined every day rather than only once and applied for several weeks as in 2009. Whereas irrigation rates were different between DWU treatments and the control on every day in 2009, irrigation volumes in 2010 DWU treatments were only lower than the control on days 414 and 462 by 46% and 41%, (Figure 2.5). Recovery volume did not differ on any day in 2010.

3.4. Nitrates and Phosphates

Effluent concentrations of NO_3^--N tended to be low early and late during the production periods while peaking in the middle of both seasons (Figure 2.6). In 2009, this peak occurred on day 39 for the 100% DWU rate at 35.8 $mg{\cdot}L^{-1}$ and 39.3 $mg{\cdot}L^{-1}$ for 75% DWU while the control peaked on both days 39 and 40 at 17.2 $mg{\cdot}L^{-1}$ (Figure 2.6). Therefore, peak NO_3^--N concentrations reached nearly four times as high as the EPA

Figure 2.6. NO_3^--N concentration in 2009 (A) and 2010 (B) and NO_3^--N quantity in 2009 (C) and 2010 (D) for runoff collected from 3m x 6m production areas (projected to g ha^{-1}) from 25 June (day 0) to 16 October 2009 and 7 June (day 348) to 31 October 2010 (day 494) for 4 conifers growing in 10.2 L containers. Fertilizer was applied on 22 June 2009 and 6 June 2010.



On days with 2 bars, irrigation was scheduled for all DWU treatments at 100% DWU replacement. On days with 3 bars, 100-75 and 100-75-75 treatments were scheduled for 75% DWU replacement. Control irrigation volume = 190 x 10^3 L·ha^{-1} applied daily. Uppercase letters indicate means separation between measurement days within each treatment (α = 0.05, 2009 Control and 100% DWU: n=6; 75% DWU: n=3, 2010: Control

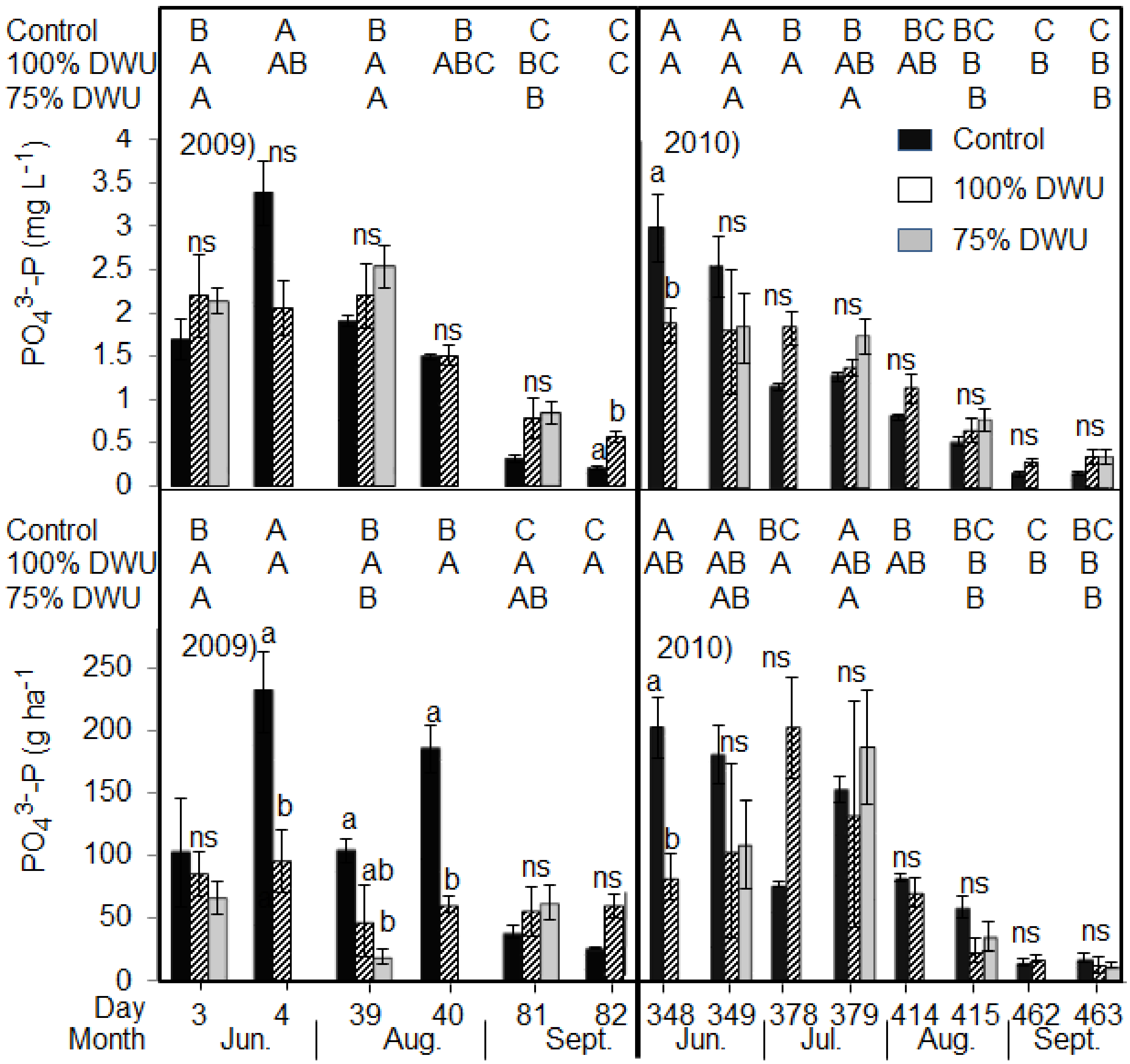
Figure 2.6 (cont'd)
and 100% DWU: n=8; 75% DWU: n=4). Lowercase letters indicate means separation between treatments within each measurement day. Means separation performed using Tukey's Test (α = 0.05, ns= not significant, n=3).

limit for safe drinking water of 10 $mg \cdot L^{-1}$ (Anonymous, 1986), although effluent leaving nurseries becomes diluted when joining other water bodies. Concentrations of NO_3^--N recovered in the 100% DWU and 75% DWU basins were over twice as high as concentrations in the control basins on day 39 because irrigation rates applied to the control were higher than both the 100% DWU and 75% DWU irrigation applications, (Figures 2.5 and 2.6).

In 2010, peak NO_3^--N concentrations occurred on day 378 at 19.9 $mg \cdot L^{-1}$ for the 100% irrigation applications and on day 379 for the 75% applications at 22.9 $mg \cdot L^{-1}$and control at 16.6 $mg \cdot L^{-1}$ (Figure 2.6), which, although less than concentrations observed in 2009, still represent an approximately twofold increase above the EPA limit (Anonymous, 1986). The lowest concentrations occurred on days 462 and 463 (Figure 2.6). On day 348, concentration of NO_3^--N was greater in the control than for the 100% DWU and greater than the 75% DWU irrigation on day 349 (Figure 2.6). Differences in NO_3^--N concentrations did not occur on any other days in 2010. In both seasons, peak effluent recovery was observed around 30 d after fertilizer applications were made.

The effluent NO_3^--N load was greater for the control than the 100% DWU on days 4 and 40 in 2009 but only day 348 in 2010 (Figure 2.6). When all three irrigation treatments were applied on day 39, NO_3^--N load from the control exceeded the 75% DWU. Similar to the response seen in 2009, nutrient loading in 2010 peaked midseason on day 378 (August) for the 100% DWU and day 379 for the other two irrigation treatments. Peak nutrient loading corresponded to peak season temperatures in August (Figure 2.2). Birrenkott et al. (2005) documented a similar controlled-release fertilizer release pattern with daily N release peaking mid-season, which they attributed to higher temperatures during that period. A season equivalent of 285 $kg{\cdot}ha^{-1}$ NO_3^--N was applied in both 2009 and 2010. Of total NO_3^--N applied, day 40 represented the highest percentages of NO_3^--N recovered in 2009 in the control and 100% DWU at 0.724% and 0.311%; however recovery in the 75% DWU did not differ between any days, although 0.06% was recovered on day 39. When only the 100% DWU and control applications were made on days 4 and 40, NO_3^--N quantities recovered in effluent were 50% and 57% lower than the control, which received the greater irrigation volume. In 2010, highest recovery of total applied NO_3^--N occurred on day 378 for 100% DWU applications at 0.783% and day 379 for control and 75% DWU applications at 0.518% and 0.897%. On day 378, NO_3^--N quantities recovered in the 100% DWU applications represented 219% of quantities recovered in the control, and on day 379, the 75% applications were 115% of quantities recovered in the control.

Figure 2.7. PO_4^{3-}-P concentration in 2009 (A) and 2010 (B) and PO_4^{3-}-P quantity in 2009 (C) and 2010 (D) for runoff collected from 3m x 6m production areas (projected to g ha^{-1}) from 25 June (day 0) to 16 October 2009 and 7 June (day 348) to 31 October 2010 for 4 conifers growing in 10.2 L containers. Fertilizer was applied on 22 June 2009 and 6 June 2010.



On days with 2 bars, irrigation was scheduled for all DWU treatments at 100% DWU replacement. On days with 3 bars, 100-75 and 100-75-75 treatments were scheduled for 75% DWU replacement. Control irrigation volume = 190 x 10^3 L·ha^{-1} applied daily. Uppercase letters indicate means separation between measurement days within each

Figure 2.7 (cont'd)
treatment (α = 0.05, 2009 Control and 100% DWU: n=6; 75% DWU: n=3, 2010: Control and 100% DWU: n=8; 75% DWU: n=4). Lowercase letters indicate means separation between treatments within each measurement day. Means separation performed using Tukey's Test (α = 0.05, ns= not significant, n=3).

Effluent PO_4^{3-}-P concentrations tended to peak shortly after nutrient applications were made. Peak PO_4^{3-}-P concentrations in 2009 occurred on day 4 for the control at 3.4 $mg \cdot L^{-1}$, while concentrations for the 100% DWU and 75% DWU were generally higher during the first four collection days than the latter two days (Figure 2.7). The only difference between irrigation treatments observed in 2009 occurred on day 82 where the PO_4^{3-}-P concentration in the 100DWU was 270% higher than the control, in which irrigation volume exceeded the 100 DWU. In 2010, PO_4^{3-}-P concentration peaked on days 348 and 349 for the control and days 349 and 379 for the 75% DWU (Figure 2.7). Effluent PO_4^{3-}-P concentrations in the 100% DWU were greater on the first three sampling days than the last three sampling days. Similarly, control and 75% DWU concentrations were lower late in the season compared to earlier. As with 2009, only one difference occurred in 2010 between irrigation treatments; the control PO_4^{3-}-P concentration exceeded the 100% DWU on day 348 (Figure 2.7). Similarly, Warsaw et al. (2009b) also reported occurrences of effluent nutrient concentrations recovered from their control being lower than 100% DWU or 75% DWU irrigation application rates.

On days 4 and 40, PO_4^{3-}-P loading of the 100% DWU application was 59% and 67% less than the control, and on day 39, loading in the 75% DWU was 81% lower than the control (Figure 2.7). Peak PO_4^{3-}-P loading occurred on day 4 for the control and 100% DWU irrigation treatment (Figure 2.7). Only one difference in PO_4^{3-}-P loading occurred in 2010 with the control exceeding the 100% DWU on day 348 (Figure 2.7). Highest PO_4^{3-}-P loading occurred on days 348 for the control, day 378 for the 100% DWU, and day 379 for the 75% DWU. Lowest PO_4^{3-}-P loading was observed during the last collection period (days 462-463) for all application rates (Figure 2.7). On day 348, quantities of PO_4^{3-}-P recovered in the 100% DWU was 63% less than the control; however, irrigation volumes did not differ.

In contrast to concentration, nutrient loading in effluent tended to increase with increasing irrigation volume. Fewer differences in NO_3^--N loading in 2010 compared to 2009 likely resulted from irrigation volumes of the DWU-based application rates and the control only differing between two of eight measurement days rather than in 2009 when the control and DWU application rate differed on every measurement day (Figure 2.5). Warsaw et al. (2009b) found that compared to their control, NO_3^--N loading in effluent was reduced, on average, 38% and 59% with their 100% DWU and 75% DWU application rates. Likewise, PO_4^{3-}-P loading in their 100% DWU and 75% DWU treatments were 46% and 74% lower than their control. Fare et al. (1994) showed that at an irrigation volume of 13 mm, 63% of NO_3^--N applied was recovered in effluent whereas only 19% was recovered under 6 mm irrigation applications. Similarly, compared to their high LF treatment of 0.4 - 0.6, Tyler et al. (1996) reported that a low

LF of 0.0 - 0.2 treatment reduced NO_3^--N and NH_4^+-N quantities recovered in effluent by 66% and 62%. Total P recovered in the effluent was 57% lower in the low LF than the high LF. These studies all indicate that increasing irrigation volume generally leads to increased nutrient quantities in nursery effluent, which supports the increased quantities of nutrients recovered from the control compared to DWU irrigation applications in the current study.

Conclusions

Both TDR and capacitance substrate moisture sensors can be incorporated into real-time automated irrigation systems to further streamline the data acquisition and control tasks required when irrigating based on DWU. DWU treatments produced the same growth as the control, except *C. obtusa* 'Filicoides', which showed increased growth in the 100DWU treatment. The relatively wide K_C ranges identified by the current study and others imply that great variation exists between the many woody ornamental crops produced by nurseries. In addition, the classification of the four container-grown taxa by water use group adds to the body of work by Warsaw et al (2009a and 2009b) and the earlier Burger et al. (1987). Grouping of plants in nursery irrigation blocks according to K_C reduces probability of over- or under-irrigation, thereby improving the use of water resources. Both Warsaw et al. (2009b) and Karam and Niemiera (1994) showed that in humid climates, scheduling irrigation to replace 100% DWU (a LF of 0) can be accomplished without EC exceeding recommended levels (above 1.5 $dS \cdot m^{-1}$, Owen et al., 2011); however, if a 0 LF is desired, EC should be frequently monitored and substrates leached whenever necessary.

The ability of the automated system to adapt to changes in DWU with daily resolution demonstrates great potential as a convenient and accurate scheduling tool. Grower-friendly systems are being developed that permit multiple sensor inputs, including soil moisture, EC, soil temperature, air temperature, relative humidity, precipitation, and photosynthetically-active radiation, in a multi-layer, self-configuring network capable of transmitting data wirelessly (Lea-Cox et al., 2008 and Lea-Cox et al., 2011). Ultimately, such accessible and flexible automated systems in the hands of growers will help them expediently make more informed production decisions (Lea-Cox et al., 2011). Some of the potential benefits of an automated sensing system were realized in the current study when irrigation applications averaged over both years to the 100DWU, 100-75, and 100-75-75 treatments were reduced by 22%, 24%, and 28%, respectively, compared to the control. Also, the 100% DWU and 75% DWU irrigation applications reduced effluent NO_3^--N loading by 36% and 67% and PO_4^{3-}-P loading by 38% and 57% when averaged over all measurement days. Not only does this translate to less eutrophication potential, but it could also save growers money in the form of fewer nutrient inputs and potentially lower energy costs for the pumping and distribution of water. DWU-based irrigation scheduling can serve as a promising solution in reducing effluent volume and the quantity of nutrients lost from production areas.

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CHAPTER THREE

CONCLUSIONS AND FUTURE RESEARCH PERTAINING TO IRRIGATION MANAGEMENT USING SOIL MOISTURE SENSORS TO LOWER WATER USE AND REDUCE RUNOFF AND NUTRIENT LOSSES IN EFFLUENT

Research Summary

Eight ornamental shrub taxa were grown from June to October 2009 to investigate three irrigation levels based on estimated daily water use (DWU) ("irrigation study"). All plants were potted the previous September in 10.2 L containers and 85% pine bark, 15% peat moss (vol : vol) substrate at the Horticultural Teaching and Research Center (HTRC) in Holt, MI. All treatments received identical cultural practices except irrigation. From 11 June to 14 October 2010, substrate volumetric water content (SVWC) was measured approximately every 3 weeks using a ThetaProbe Type ML2x (Delta-T Devices Ltd.) to calculate DWU. Four irrigation treatments were applied daily: 1) control application of 0.75 acre-inches, 2) irrigation applied to replace 100% DWU, 3) applications alternating 100% DWU with 75% DWU in a 2-day cycle, and 4) a 3-day application cycle replacing 100% DWU on the first day and 75% DWU on the second and third days. Each treatment was replicated 3 times with 6 subreplications of each taxa per treatment replicate. Irrigation treatments were applied daily via overhead irrigation to meet the needs of the lowest water user(s) with supplemental DWU requirements supplied by hand.

In 2010, eight new ornamental shrub taxa were grown from June to October using the same irrigation treatments, experimental design and methods as 2009 with a few exceptions. From June 23 to October 31, 2010, substrate volumetric water content (SVWC) was continuously monitored in each of the eight taxa using Decagon 10 HS soil moisture sensors. Plants were irrigated daily, and initial SVWC values were recorded after 1 h New SVWC readings were taken 24 hr later to calculate DWU ($DWU=SVWC_{1h} – SVWC_{24h}$) and determine irrigation treatments for the day. One subreplicate of each taxa in each treatment replicate was monitored by a Decagon 10 HS sensor for a total of 96 sensors in the study. A CR3000 Micrologger (Campbell Scientific, Logan, UT) coordinated the treatment and irrigation scheduling. Daily irrigation applications were based on the needs of the highest DWU for each treatment replicate, so all taxa in each replicate, regardless of water need, received the same amount.

Additionally, from 2009 to 2010, a related study ("runoff study") was also conducted at the HTRC to analyze the effects of the above-mentioned treatments on runoff volume and NO_3^--N and PO_4^{3-}-P concentration and load in effluent. Four conifers were grown identically to the above description, except overwintered in plastic film-covered quonset houses for continued study in 2010. Calculation of DWU was conducted using the ThetaProbe in 2009 and Decagon 10 HS sensors, also as described above. Monthly, the runoff basins were emptied, volumes measured, and water samples collected for nutrient analysis.

Daily water use treatments conserved water in both studies. In 2009, water reductions in the irrigation study ranged from 7% in the 100DWU treatment to 57% in the 100-75-75 treatment depending on species. Daily water use of high water users exceeded the control during two measurement days in August. The remainder of the plants required less irrigation than the control treatment throughout the study. Plants in the runoff study received 22%, 32%, and 35% less irrigation in the 100DWU, 100-75, and 100-75-75 treatments, respectively. Plants in neither study had decreased growth in DWU deficit treatments relative to the control, however, *Hydrangea paniculata* 'Limelight' grew larger than the control in the 100DWU treatment. The ability of the automated irrigation system to adapt to changes in DWU with daily resolution demonstrates great potential as a convenient and accurate scheduling tool.

In 2010, the 100DWU and 100-75 treatments actually received more water than the control because irrigation was scheduled based on the water needs of the highest user in each treatment replicate. However, the automated system effectively identified the highest water user each day to meet its water needs; no signs of wilt or lost growth were recorded throughout the study. However, in the 100-75-75 treatment, *Hydrangea paniculata* 'Limelight' was smaller than the other treatments, probably because overall irrigations in that treatment were 52% less than the control.

Daily water use of the runoff plants decreased relative to the first year, possibly because DWU was determined from daily calculations. However, throughout most of the season, *Chamaecyparis obtusa* 'Filicoides' was larger in the 100DWU treatment than the control. These observations further substantiate the results of Warsaw et al., (2009a and b) that irrigating according to DWU conserves water, that under moderate cumulative moisture stress plants possess a buffer against decreases in growth, and that growth can be increased when scheduling according to DWU relative to time-based approaches.

Continuous sensor data from 2010 provided insight into daily changes in DWU of each species. Crop coefficients (K_C) were calculated from this data and averaged over each month of the study. This revealed a consistent pattern with K_C beginning consistently low for each taxa in spring, increasing until mid-season, and leveling off toward the end of the season. However, K_C of individual taxa increased variably so that by mid-summer, K_C could be used to rate plants as low, moderate, or high water users. In the 2006 - 2008 growing seasons, Warsaw et al. (2009 a) classified 24 plants using K_C at the HTRC, so this project adds 17 new K_C to their work. Over five years, "indicator" species have now been identified to help group plants into irrigation blocks at nurseries enabling irrigation to be applied more precisely based on plant need. Because these K_C were developed over the course of different seasons, there were some inconsistencies between the same taxa over different years. However, these K_C still provide a useful ranking of species water needs for others to follow. In addition, monthly values were reported in 2009 and 2010, which help provide an understanding of how the water needs of container-grown shrubs change over a production season. Since container plants are often re-spaced during production, K_C values for ornamental shrub taxa could be published by month or stage of growth to further aid in grouping as they are moved from one production area to another.

Effluent volume was reduced at lower irrigation rates. In 2009, differences in runoff volume collected were clear between each treatment because the same amount of water was applied in each treatment replicate, and 75% fractions were based on the same DWU calculations (averaged over every taxa replicate) as 100% fractions. However, in 2010, the DWU was based on the highest water user in each treatment replicate. Since less water was generally applied in the DWU treatments, they also tended to produce lower runoff volumes. Because of these lower runoff volumes, NO_3^--N and PO_4^{3-}-P concentrations tended to be higher in DWU treatments. However, bulk nutrient quantities recovered in effluent were generally higher at increasing irrigation volumes. This would intuitively indicate that CRF fertilizers were being depleted, which may have contributed to the decreased growth in the control across both studies relative to the lower-volume DWU treatments.

Foliar nutrient analysis revealed noteworthy differences between treatments. In every case that a difference occurred, the control had lower %P or %K than plants in the DWU treatments. Following the depletion of substrate nutrients, dilution of nutrients may occur in new plant tissues (Tyler et al., 1996). Since the runoff study shows greater nutrient recovery from production beds irrigated at high volumes, it can be presumed that fertilizer was also being leached from rooting substrates at higher rates in the control compared to DWU treatments in the irrigation study as well. Additionally, pH measurements in the irrigation study increased over time due, likely due to high pH and alkalinity of the irrigation water. However, higher-volume irrigation treatments often had higher pH at conclusion of both seasons. Consequently, reductions in water applications improve nutrient efficacy and can help minimize the effects of the irrigation water itself on substrate chemistry.

Particular insight was gained from using the two different sensor designs over two seasons. Whereas the thin metal rods of the ThetaProbe (TDR) easily punctured the substrate matrix and demonstrated good repeatability when reinserted in the same position, the wide blades of the Decagon capacitance sensors made insertion difficult at times. Large particles of pine bark or clumps of peat necessitated probe reinsertion in different positions within containers for *in situ* monitoring. Although sensors were inserted when substrate was moist to minimize the introduction of air pockets, the initial data suggests that poor substrate-sensor contact was achieved. Fortunately, the probes were inserted into the substrate weeks prior to the beginning of both studies while plants were watered regularly. This apparently helped the substrate settle for a more uniform contact with the probes as their outputs became more consistent prior to treatment initiation. Still, several sensors reported out of range values, which prompted us to perform substrate-specific calibrations in the field. Sensors were left undisturbed *in situ*, and a dry-down was performed over two days (see appendix section). The resulting calibrations responded much better to changes in SVWC and were put into use for the duration of the two studies.

Future Research

In the last several years, wireless sensor networks (WSN's) have been in development between several institutions involved in both software and hardware engineering and testing (Lea-Cox, et al., 2013). During the development of their system, we provided our experience in using the sensors to measure DWU in container-grown shrubs. In addition, the authors have begun tests at commercial nursery operations in which they have received feedback from several enthusiastic growers. This feedback has led to the development of software that is easily configured to provide custom data output for data monitoring and irrigation control at the user's discretion (Kohanbash et al., 2013). Similar to our system, their approach involves the use of user-defined irrigation set points. To accommodate changing management and production objectives (such as pesticide applications, pruning, pulling plants for shipping, etc.), the program also features a suspend mode to ensure irrigation will not activate at undesirable times.

These systems still represent a significant capital investment beyond the means of smaller operations (Lichtenberg et al., 2013), so it will take years to achieve widespread adoption by nurseries. In addition, many individual nurseries produce hundreds of cultivars on relatively large acreages, which likely means that direct measurement of substrate moisture for every plant grown by nurseries will not be possible in the foreseeable future (Lea-Cox et al., 2013). This emphasizes the importance of continuing to classifying plants according to water use groupings. Now, a few dozen K_C exist for temperate ornamental shrub taxa that can serve as "indicator" species of relative water requirement, but currently no action has been taken to formally define water use groups. As water use data is continually collected, water use classes will become better defined as taxa, container size, substrate properties, growth rate, phenological stage, season, and climate can all affect plant water needs.

Additionally, the development of K_C for each of these taxa provides the opportunity for the development of models to determine actual evapotranspiration (ET_A) using easily-measured parameters at the nursery site such as growth index, or percent canopy closure (Beeson, 2010). A single model developed for *Ligustrum japonicum* has been shown to successfully predict the water needs of *Viburnum odoratissimum* using percent canopy closure (Beeson, 2010). Consequently, the construction of various models to describe the water needs of a particular type or group of plants presents another technique for grouping plants into irrigation groups. As with all models, these will have to be validated in real-world production conditions before achieving widespread adoption.

Water has become a major topic in media, and agricultural water use is particularly sensitive to widespread water shortages where the majority of crops are irrigated. Each agricultural operation can take steps appropriate for their size and crops to conserve water. Ornamental plant producers now have several options at their disposal to reduce water consumption, including using sensors to determine DWU, development of weather-based models, and improving irrigation application equipment. Reducing water withdrawals will also reduce nutrient movement offsite to protect our public water bodies. Growers who seek out new technologies and practices will likely be rewarded as environmentally-conscious customers recognize their commitments to environmental stewardship and choose to do business with them.

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