USE OF NEAR-ZERO LEACHATE IRRIGATION SYSTEMS FOR CONTAINER PRODUCTION OF WOODY ORNAMENTAL PLANTS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for

the Degree of Doctor of Philosophy in the Graduate

School of The Ohio State University

By

Jonathan D. Sammons, B.A., M.S.

*****

The Ohio State University
2008

Dissertation Committee:

Dr. Daniel K. Struve, Advisor

Dr. James Metzger

Dr. Hannah Mathers

Dr. Robert Hansen

Approved By

____
Advisor
Graduate Program in Horticulture
and Crop Science

ABSTRACT

Increased environmental awareness combined with a decrease in available water for irrigation has required the nursery industry to evaluate water and nutrient efficiencies. The production of plants in containers reduces the rooting volume available to the plant by about 95% resulting in a limited reservoir of moisture and nutrients. The substrates most commonly used in container production are soilless and porous, with pine bark comprising all or at least a majority of the substrate. This production environment requires nursery producers to irrigate daily to maximize plant performance. As irrigation volume increases both water and nutrient efficiencies decrease. This work investigates the interactions of irrigation, fertilizer rate, and water and nutrient efficiencies.

A plant-integrated, gravimetric, substrate moisture monitoring system was used to control irrigation volume and limit leachate volumes to near-zero levels. Effective container capacity (ECC) was used to determine irrigation volumes and frequency. ECC was defined as the maximum mass of the container, substrate and plant unit after gravitational water loss. The system used the ECC target to deliver irrigation within a narrow range of substrate moisture contents to study the effects of irrigation volume on growth, water use, and nutrient uptake of baldcypress (*Taxodium distichium* L.).

In the summer of 2006, the gravimetric substrate monitoring system was proven as an effective, plant-integrated method of reducing leachate volume that required minimal maintenance under the four month experimental period. Under a near-zero leachate irrigation system, irrigation volume and leachate volume (by definition) are decreased; substrate nutrient concentration was increased resulting in increased plant tissue nutrient concentration, and an increase in water-use efficiency. Nitrogen use efficiency was not affected by irrigation regime in this study, as fertilizer rate impacted uptake of nitrogen.

DEDICATION

This work is dedicated to my wife, Abby Sammons.

ACKNOWLEDGEMENTS

I wish to thank my main advisor, Dr. Dan Struve, for his guidance throughout my term at Ohio State and for providing me the opportunity to pursue this degree. This work is rooted in Dan's extensive knowledge of the nursery industry and was nurtured by his encouragement, patience, and financial support.

I would like to recognize Tom Kruer for his encouragement and financial support.

I wish to thank my committee members for their support and time over the past four years.

I wish to thank both, Jim Vent and David Snodgrass for providing an environment conducive for my research efforts and the comic relief along the away.

I wish to thank my family for their example, their continued encouragement and their dedication to my success.

VITA

March 3, 1978………………………………Born-Dayton, Ohio

2000…………………………………………B.A., Miami University

2002-present……………………………......Graduate Research Associate
The Ohio State University

2004…………………………………………M.S., The Ohio State University

PUBLICATIONS

Sammons, J.D. and D.K Struve. Effect of Bioplex™ on Transplant Success of Non-Dormant Red Oak (*Quercus rubra* L.). 2004. Journal of Environmental Horticulture 22(4):197-201.

Sammons, J.D. and D.K Struve. Effect of Bioplex ™ on Transplant Success and Recovery of Summer-Dug Goldenraintree. 2005. Journal of Environmental Horticulture 23(2):59-62.

Sammons, J.D. and D.K Struve. Monitoring Effective Container Capacity: A Method for Reducing Over-Irrigation in Container Production Systems. 2008. Journal of Environmental Horticulture 26(1):19-23.

FIELD OF STUDY

Major Field: Horticulture and Crop Science

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE PAGE

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The practices of fertilization and irrigation control the rate of plant growth for container-grown plants more than any other cultural practice (Landis 1989). For this reason, nursery producers have applied water and fertilizers in copious amounts to maximize plant growth. With the typical soil-less, porous, substrates used in container production the result has been the inefficient use of irrigation and nutrients due to excessive leaching; leachate nitrate-nitrogen concentrations from container grown plants periodically exceeds 10 mg/liter (Yeager and Cashion, 1993). Increased environmental awareness, competition for water and increasing economic cost of fertilizers has demanded research to improve both water and nutrient use efficiencies (Beeson et al, 2004).

For container-grown plants the rooting volume is limited, compared to the rooting volume available to a field grown plant. This limited rooting volume can be quickly depleted of moisture and nutrients by a rapidly growing plant. To combat this problem nursery producers must supply the substrate daily with suitable moisture and nutrients. Typically growers will irrigate one to two times a day and supply mineral nutrients through fertigation, a controlled release fertilizer (CRF), or a combination of the two.

Fertilizer effectiveness relies on adequate potting substrate moisture; as substrate moisture is reduced so is the effectiveness of the fertilizer application (Squire et al., 1987). Because the most common fertilizers used in container nursery production are inorganic (inorganic fertilizers are chemically considered salts) low substrate moisture can result in soluble salt damage to plant roots; the damage can be described as osmotic dehydration. Soluble salt levels can be evaluated by measuring electrical conductivity (EC) levels of the substrate. EC levels can be lowered either through plant uptake or by leaching (Landis, 1989). Conversely, once nutrient ions are in the soil solution they are subject to leaching. If irrigation volume exceeds container capacity, 80-90% of available nitrogen can be lost to leaching (Foster et al., 1983).

Leaching in nursery container production is exacerbated by the low cation exchange capacity (CEC) of the typical production substrates (Tyler et al., 1996a). Most nursery container substrates are composed primarily of pine bark. Uncomposted bark has an average CEC of 11-13 meq 100 cm^{-3}, compared to 5-15 for sandy soils or 25-30 for clay soils (Bunt, 1988). Thomas and Perry (1980) reported for a 1 gallon container with a pine bark based substrate 90% of ammonium-nitrogen was loss after a 5.5 liter irrigation event. Pine bark substrates also have a low anion exchange capacity (AEC) which allows nitrate-nitrogen to leach freely (Tyler et al., 1996a). CRF has been used to reduce leaching of available nitrogen; leached nitrogen with CRF has been reported between 12 and 29% (Tyler, 1996a). Groves et al. (1998) showed that substrate nitrate- and ammonium-nitrogen concentrations decreased as irrigation volume increased with a CRF fertilizer, this result was due to excessive leaching. Improving irrigation and nutrient efficiencies in container nurseries requires an understanding of the interaction of various irrigation and fertilizer practices.

FERTILIZER TYPES AND PLANT UPTAKE

In container nurseries two types of fertilizers are used; soluble fertilizers and controlled release fertilizers (CRF). Soluble fertilizers are applied directly into the potting substrate by a process known as fertigation (Landis, 1989). Fertigation is the practice of providing nutrients to plants in the form water soluble fertilizer injected into the irrigation water. However, this technique can be very inefficient, especially if paired with over-head irrigation practices. Efficiency rates of over-head irrigation will be discussed later. CRFs are fertilizer products that slowly reslease their nutrient packages into the surrounding potting substrate. CRFs provide more efficient delivery of nutrients than liquid feed. Sanderson (1987) estimated that ten times more nutrients are lost with liquid feed than with CRFs. The increase in efficiency of CRFs is due to the prolonged release of nutrients over the growing season.

There are three types of CRFs; coated water-soluble fertilizers, inorganic fertilizers of low solubility, and organic fertilizers of low solubility (Landis, 1989, Sanderson 1987, and Bunt 1988). Osmocote is an example of a coated water soluble fertilizer. Coated CRFs contain dry nitrogen, phosphorus, and potassium (N-P-K) inside a plastic resin. Inorganic fertilizers of low solubility are extremely insoluble and can even withstand exposure to steam sterilization without nutrient release, release rates can be so slow that they are not suitable for some ornamental plants, their release rates are a function of particle size (Landis, 1989 and Sanderson, 1987). Oraganic fertilizers of low solubility are composed of urea-formaldehyde fertilizers, their release rates are caused by hydrolysis and biological activity; pH, temperature, and microorganism population each effect release rates (Landis, 1989, Sanderson 1987).

Coated water-soluble fertilizers are the most common CRFs used in container nursery production. These CRFs are coated with a polymer that is the responsible for the release rate; the polymers are typically a sulfur, a polymeric substance or a combination of both (Goertz, 1993). These fertilizer types have also been called polymer-coated fertilizers or PCFs (Goertz, 1993). The polymer coating forms a semi permeable memebrane that allows water vapor to difuse into the capsule, the vapor then condenses and dissolves a portion of the soluble fertilizer, the dilute fertilizer then moves out of the membrane by diffusion or hydrostatic pressure (Goertz, 1993 and Bunt, 1988).

For horticultural crops, nitrogen (N) is the dominant nutrient in the growth, development, productivity, and longevity of a plant (Huett, 1996) and therefore of most concern to growers. Argen and Ingsted (1987) proposed that plant growth is a function of nitrogen content, meaning plant growth is determined in part by nitrogen availability. Unfortunately, this finding can be interpreted as meaning, more nitrogen equals more yield, and does not take into account nutrient uptake efficiency (NUE). NUE is defined as the amount of nutrients accumulated by the plant divided by the total amount of nutrients applied (Craig, 2001).

Supplying plants with more nutrients than is required to maintain optimal growth is termed luxury consumption (Landis, 1987). For some species luxury consumption may result in nutrient loading. Nutrient loading is characterized as an increase in plant tissue nutrient concentration without an increase in plant dry weight (Malik et al., 1995). Nutrient loading has been observed in black spruce (Malik et al. 1995), red maple (Larimer and Struve, 2002), and *Cercis siliquastrum* (Zahreddine et al., 2007). The benefit of nutrient loading is improved plant performance following transplant (Malik et al., 1995).

Fertlizer rates could be estimated using plant size to increase NUE; researchers have shown nutrient uptake potentials to be highly correlated to plant dry weight accumulations (Struve, 1995, Struve and Rose, 1998, Rose and Biernacka, 1999). While there may be a correlation between plant size and nitrogen tissue concentration, plant uptake may not occur uniformly over the growing season.

Proper timing of nutrient application may improve NUE and maximize plant growth. Nutrient uptake may be greatest during times of root growth (Yeager et al. 1980). For species with episodic growth patterns, root growth occurs opposite of shoot growth, this cycle could allow for the appropriate timing of fertilizer application and increase NUE (Gilliam and Wright, 1978). Gilliam and Wright (1978) reported that for plants with multiple flushes growth was optimal if fertilizer was applied following the cessation of stem elongation. However, plant nutrient uptake has not been fully modeled for container nursery production. To maximize NUE fertilizer application rates should match plant uptake potentials. Until plant nutrient uptake patterns are better understood, the best way to improve NUE is through refining irrigation rate and delivery techniques (Struve, 1995).

IRRIGATION

In the area of nursery container production, the importance of water conservation was highlighted as early as 1988 (Urbano, 1989). Since then several studies have examined techniques to improve water and nutrient conservation with a focus on container production. The result of this research has provided a move toward precision irrigation, applying only the volume of water needed for the crop over a small surface area (Beeson, 2005). Precision irrigation is widely adapted in other agriculture sectors. However, with respect to precision agriculture in container nursery production, few practices have changed since the 1960's (Beeson, 2002).

Much of the research conducted in this area has focused on improvements in water application efficiency (WAE). WAE can be calculated as: ((water applied – water leached) ÷ water applied) (Warren and Bilderback, 2005). In an effort to increase WAE research has focused on two factors; irrigation delivery and pulse versus cyclic irrigation.

IRRIGATION DELIVERY

Irrigation delivery involves the mechanism by which water is applied to the substrate surface. For nursery container production irrigation water is most typically applied by overhead irrigation or micro-irrigation.

Overhead irrigation is currently performed on production blocks with containers < 20 L (#5 [American National Standards Institute (ANSI), 1996]) due to prohibitive maintenance and labor costs (Beeson and Knox, 1991 and Bilderback, 2002). Although, the use of micro- or drip irrigation systems have been used effectively on smaller containers at The Ohio State University (OSU). Weatherspoon and Harrell (1980) reported WAE of only 13% to 26% with overhead irrigation, with the variation attributed to sprinkler type. Irrigation water not reaching the substrate surface is primarily lost as runoff in the between pot spaces. These low efficiencies require nurseries to apply excessive amounts of irrigation above what is required to maintain adequate plant growth.

The factors influencing WAE with overhead irrigation include: overhead irrigation design, pot spacing, pot size, canopy characteristics, sprinkler type, and wind (Beeson and Knox, 1991 and Furuta, 1976).

Microirrigation consists of a low-pressure irrigation system with emitters that deliver irrigation directly to production containers (Furuta, 1973). The emitters can be point source, line source, or micro-sprinkler types (Regan, 1997). The WAE of micro-irrigation systems have been reported to range from 44% to 72% (Weatherspoon and Harrell, 1980). Irrigation water that is lost as runoff in micro-irrigation systems is primarily lost as leachate from production containers. Excessive leaching of production containers under micro-irrigation systems results from the combination of porous, soil-less container substrates and high irrigation application rates from emitters (Lamack and Niemiera, 1993). Application rates of micro-irrigation emitters can be as much as 15 times greater than overhead irrigation application rates (Lamack and Niemiera, 1993). These high rates limit the amount of lateral water movement and increase channeling in the container substrate (Hoadley and Ingram, 1982).

PULSE VS. CYCLIC IRRIGATION

Cyclic irrigation relies on the intermittent application of irrigation water in cycles. The cycles consist of an application period and a rest period. Whitesides (1989) first reported the use of cyclic irrigation in a container nursery; water use at El Modeno Gardens in Irvine, California was reduced by 30% using cyclic irrigation. And Sneed (1996) reported that cyclic irrigation reduced water use by 25%.

Cyclic irrigation is an effective method to increase WAE with both micro- and overhead irrigation systems (Warren and Bilderback, 2005). Several papers document the benefits of cyclic irrigation with both micro- and overhead irrigation systems (Table 1).

The use of cyclic irrigation has also been shown to increase plant growth when compared to one irrigation event per day (Beeson and Haydu, 1995; Beeson and Keller, 2003; Keever and Cobb, 1985; Warren and Bilderback, 2002). Increased plant growth under cyclic irrigation can be attributed to reduced daily-accumulated plant water stress (Beeson and Keller, 2003). Most container production mixes are composed of porous substrates with low water retention characteristics (Warren and Bilderback, 2002). Once plant roots have exploited the substrate volume, whole plant water use can quickly decrease substrate moisture contents to below levels for optimal plant growth, resulting in plant water stress. Keever and Coob (1985) credited increased plant growth to reduced substrate temperatures with cyclic irrigation. Heat load in black plastic nursery containers is caused by the high energy absorption rates from the sun (Ruter, 1988). Any practice that reduces substrate temperatures will increase WAE and plant growth (Mathers, 2005), due in part to the increased and more uniform root distribution in the container.

Zur (1976) examined pulse irrigation and described the application rate as being a time-averaged application rate (TAAR). TAAR is calculated as the volume of irrigation applied ÷ cycle duration (Zur, 1976). The cycle duration is the time period between consecutive initiations of irrigation.

With cyclic irrigation, TAAR is independent of water volume and number of cycles (Lamack and Niemiera, 1993; Ruter, 1998, Tyler et al.; 1996, and Warren and Bilderback, 2005), as few as, two (Bilderback, 2005) or three (Mathers, et al., 2005) cycles combined with the appropriate TAAR can increase WAE. Lamack and Niemiera (1993) showed that WAE increased from 62% to 86% as TAAR decreased from 7.5 to 0.9 ml min^{-1}, respectively. A TAAR of <10 ml min^{-1} is recommended to significantly decrease WAE (Bilderback, 2005).

IRRIGATION SCHEDULING AND MINERAL NUTRIENTS

Irrigation scheduling refers to how much irrigation to apply and when to apply the irrigation (Warren and Bilderback, 2005; Warren and Bilderback, 2004). The ideal way to schedule irrigation is to measure how much water the plants are using and then replace that amount, this strategy would be defined as precision irrigation. Several studies have examined various methods and recommendations for estimating irrigation amounts.

Bilderback et al. (1999) suggested irrigation volumes be adjusted based on EC readings. They proposed EC readings be taken weekly and irrigation volumes adjusted based on meeting a targeted EC reading of 0.85 dS m^{-1}. Due to rainfall target EC levels were not reached with any of the fertilizer rates; the conclusion was that EC readings alone were not an adequate parameter to guide irrigation volumes.

Other studies have examined the use of ET-modeling and crop coefficients to estimate crop water requirements (Bauerle, et al. 2002; Fitzgerald, 1983; Shuch and Burger, 1997). ET-modleing uses environmental parameters to estimate the water requirements of a reference crop or standard. Then crop coefficients are determined empirically, which predict the water demand of the production relative to the reference crop. Both, Fitzgerald (1983) and Bauerle (2002) have successfully demonstrated ET-modeling. However, Schuch and Burger (1997) showed ET-modeling is dependent on geographic production location, production crop, and period of the growing season limiting the robustness. Also, the practical application of ET-modeling requires equipment not found in most production nurseries and expertise beyond that of most nursery managers.

Several researchers have examined the use of plant water stress indicators to control irrigation events. Some parameters studied include: changes in stem or trunk diameter and leaf water potential (Riviere and Chasseriaux, 1999); sap flux measurements (Sakuratani, 1981; Valancogne and Nasr, 1989); and canopy temperature (Wanjura et al. 1995). However significant lag times between stress onset and plant response, and the required expertise and tools to monitor these events, have limited commercial adoption.

Another approach monitors the substrate moisture content. Various instruments have been used to monitor soil moisture (Topp and Davis, 1985; Abraham et al., 2000;

Nemiali and Irsel, 2002; Hansen et al.2006), but none of them have been widely adopted for nursery production. Also, substrate moisture content is not evenly distributed within a container (Atland, 2006); thus placement and orientation of the sensor is critical and has not yet been determined.

Welsh and Zajicek (1993) used management allowed deficits (MAD) to guide irrigation scheduling. Predetermined substrate moisture content levels, expressed as a percent of container capacity (CC), or MAD were used. Production containers were weighed gravimetrically twice daily; once the MAD level was reached the containers were irrigated to bring the container back to CC. The study was conducted using *Photinia* x *fraseri* (Dress). Plant growth was maximized under the 25% MAD treatment. MAD levels included 0, 5, 10, 25, 50, 75, and 95%.

Gonzalez et al. (1992) describes a computer controlled irrigation monitoring system that used the presence of leachate to terminate irrigation events. They report a reduction in irrigation volume of at least 95% with their system as compared to their manual irrigation control. However, the moisture sensors used to detect leachate were considered too labor intensive for commercial application.

Many studies have focused on the use of leachate fractions (LF) to guide irrigation volumes. LF is calculated by the (volume of irrigation leached ÷ volume of irrigation applied) (Warren and Bilderback, 2005). Tyler et al. (1996b) showed that a low LF reduced irrigation volume, leachate volume and leached N by 44%, 63% and 66%, respectively, compared to a high LF, but with a 10% reduction in plant growth.

The LF recommendation centers on the accumulation of soluble salts in the rooting medium resulting in elevated electrical conductivity (EC) levels that can damage plant roots. The use of a LF is borrowed from floriculture where high rates of liquid fertilizer are applied with each irrigation (Ku and Hershey, 1992). But because woody plant production involves the use of CRF and outdoor production with plentiful rainfall, LF may not be needed (Warren and Bilderback, 2005). In fact, the use of high LF can deplete CRF materials within 100 days of application (Ruter, 1992; Yeager et al. 1993; Yeager and Wright, 1982). The use of an elevated LF results in a decrease of WAE and nutrient use efficiency (NUE). The use of LF does not effectively address, how much irrigation and when to apply.

In container production of nursery crops improved WAE can result in reduced nitrogen (N) leaching (Table 1). Current best management practices for determining irrigation volume state it should be based on the amount of water lost since the last irrigation (Yeager et al. 1997). The classical way to determine water use is gravimetrically. Additionally, gravimetric monitoring is the standard by which the previously mentioned methods are judged. Adaptation of current technology will allow for the real-time gravimetric monitoring of whole plant water use.

For container-grown plants, the combination of container geometry and substrate physical properties dictates the maximum volume of plant-available water. The amount of water held by a substrate following saturation and gravitational water loss is termed container (field) capacity (Fontena, 1989 and White and Mastalerz, 1966). Container capacity can be determined gravimetrically. If substrate moisture content were monitored gravimetrically in real-time, then irrigation could be applied to plants within a narrow range of substrate moisture contents, resulting in 100% WAE. Also, maintaining substrate moisture content at or near 100% container capacity will also increase plant growth (Beeson and Haydu, 1995 and Beeson, 1992).

Accumulation of soluble salts under near-zero leachate irrigation is of concern. However, Tyler et al. (1996a) showed that fertilizer release rates exceed that of plant uptake for the two rates tested. This suggests fertilizer rate could be reduced without consequence to plant growth. By matching fertilizer rate to plant uptake potential, plant injury to soluble salts could be reduced, even under near-zero leachate fractions.

Irrigation Delivery	WAE % Increase	Leached N % Decrease	Author(s)
Overhead	34	17	Fare et al., 1994
Overhead	5-10	66	Karam and Niemiera, 1994
Micro-	38	-	Tyler et al., 1996a
Micro-	-	62-66	Tyler et al. 1996b
Micro-	24%	-	Lamack and Niemiera, 1993

Table 1.1. Percent increase in water application efficiency (WAE) and Percent decrease in leached N under cyclic irrigation compared to a single application.

CHAPTER 2

MONITORING EFFECTIVE CONTAINER CAPACITY: A METHOD FOR REDUCING OVER-IRRIGATION IN CONTAINER PRODUCTION SYSTEMS

ABSTRACT

A gravimetric substrate moisture monitoring system was used to control irrigation frequency and volume within a narrow range of substrate moisture contents to study the effects of reduced irrigation volume on growth and water use of baldcypress (*Taxodium distichium* L.). The four irrigation treatments were: control (daily scheduled irrigation at 16:30 hours for 15 minutes or 6.75L (1.74 gal) day^{-1}) and 100, 80 and 60% of effective container capacity (ECC). Effective container capacity was defined as the maximum mass of a container, substrate and plant unit after gravitational water loss. Maintaining substrate moisture content at 80 and 60% ECC reduced baldcypress height, caliper, dry weight, and total plant N, P, and K content, but did not effect N, P or K concentrations compared to scheduled irrigation and 100% ECC treatments. Water use efficiencies (WUE, the volume of irrigation lost to evapo-transpiration divided by the total volume of irrigation applied) were determined for three dates. Plants under scheduled irrigation had

WUEs of 17, 33, and 42% on July 8, July 24, and August 16, respectively. In contrast, WUE for plants under 100, 80 and 60% ECC treatments was 100% (no leachate) for the same dates. Plant water use under 80 and 60% ECC treatments was lower than that under scheduled and 100% ECC treatments. Plants under the 100% ECC treatment were 1.6 m (63 in) tall in August and used 2.6 L (0.68 gal.) of water per day. The gravimetric substrate monitoring system was an effective, plant-integrated method of reducing leachate volume that required minimal maintenance under the four month experimental period.

INTRODUCTION

Water is becoming one of the world's most precious resources. Legislation requiring nurseries to protect and preserve clean water has been enacted in several southern and western states. In Florida, legal restrictions in 2004 limited nursery irrigation amounts by 40% compared to 1992 levels, and tighter restrictions are likely due to the Clean Water Act (Bauerle et al. 2002). Thus, nursery producers must develop production methods that use less water without sacrificing plant growth or quality. Increasing the efficiency of irrigation delivery is one method of increasing water application efficiency. Water-application efficiency has been defined as the amount of water stored in the root zone compared to the total amount of water applied (Israelsen and Hansen, 1962). In container production, 100% water-application efficiency equates with zero leachate.

A major increase in water-application efficiency occurred when growers shifted from overhead to micro-irrigation. For example, overhead irrigation application efficiencies ranged from 12-50% (Beeson and Knox, 1991) while micro-irrigation application efficiencies ranged from 44 to 72% (Lamack and Niemiera, 1993).

Cyclical or pulse irrigation (irrigating containers for several short periods with lower volume), compared to one or two irrigation events per day increased both water-application efficiency and plant quality (Beeson and Keller, 2003, Keever and Cobb, 1985, and Warren and Bilderback, 2002). Increased plant quality was attributed to reduced daily accumulated plant water stress (Beeson and Keller, 2003) and to reduced substrate temperatures (Keever and Cobb, 1985). Increased water-application efficiency was attributed to increased lateral water movement (or alternatively, decreased channeling) in the substrate (Lamack and Niemiera, 1993). An alternative approach is the Multi-Pot Box system that increases irrigation water use efficiency by capturing rainfall and excess irrigation in reservoirs with later delivery to the crop via sub-irrigation (Irmak et al. 2001).

Water-application efficiency could be further increased if an efficient irrigation delivery system is coupled with a plant-integrated monitoring system. One monitoring approach uses relative ET-modeling and crop coefficients to estimate crop water needs (Schuch and Burger, 1997). The ET-modeling approach has not been widely adopted because crop water coefficients are specific to each crop, production location, and period of the growing season (Schuch and Burger, 1997). Modeling container crop water use has been demonstrated (Bauerle et al., 2002), but its practical application requires equipment not found in most nurseries and technical expertise beyond that of most nursery managers. Others have used plant water stress to control irrigation events; however significant lag times between stress onset and plant response have limited commercial adoption (Devitt et al., 1993, Morianna and Fereres, 2002, Ton and Kopyt, 2003, Wanjura et al., 1993).

Another approach monitors the substrate moisture content. Various instruments are available to monitor soil moisture (Abraham et al., 2000, Nemiali and van Iersel, 2002, Topp and Davis, 1985), but none have been widely adopted for nursery production. Also, substrate moisture content is not evenly distributed within a container (Altland, 2006); thus the appropriate location and orientation of substrate moisture sensor probes has not been determined.

For container-grown plants, the combination of container geometry and substrate physical properties dictates the maximum volume of plant-available water. The amount of water held by a substrate following saturation and gravitational water loss is termed container (field) capacity (Fonteno, 1989 and White and Mastalerz,). Container capacity can be determined gravimetrically. If substrate moisture content were monitored gravimetrically in real-time, then irrigation could be applied to plants within a narrow range of substrate moisture contents, resulting in 100% water application efficiency. Also, maintaining substrate moisture content at or near 100% container capacity will also increase plant growth (Beeson and Haydu, 1995 and Beeson, 1992).

The objective of this study was to determine if gravimetric monitoring of a plant-substrate-container unit could be used to manage irrigation volume on a real-time basis and to study the effect of reduced irrigation volume on baldcypress (*Taxodium distichium* L.) growth, water use, and nutrient uptake.

MATERIALS AND METHODS

PREPERATION OF PLANT MATERIAL

In spring of 2004 recently germinated baldcypress seedlings were transplanted into 14 cm square, 15 cm deep (5.5 by 6.0 in.) Spinout®-treated (Griffin Corp.,Valdasta, GA) plastic containers (250XL Nursery Supplies, Fairless Hills, PA) at the Howlett Hall greenhouses located on the Columbus campus of The Ohio State University. The substrate was Metro Mix 360 (Sun-Gro Horticultural Bellevue, WA). Seedlings were maintained weed free and watered twice daily with 100 ppm of 21N-2.9P-4.3K (21-7-7 Peters, Scotts Miracle-Gro Co., Marysville, OH) water-soluble fertilizer until September, when they were moved to a minimum heat polyhouse (4.4 C [40 F]) until the spring of 2005.

Forty baldcypress seedlings, selected for uniformity (height and caliper), were transplanted to #15 containers (Model No. 54.31l, [44.5 cm dia. by 40.6 cm deep (17.5 by 16 in.) or 54.5 L (14 gal)], Engineered Resins, Charlotte, NC) on June 1, 2005 and placed on a gravel production pad on the Columbus campus. The substrate was a pine bark, composted municipal sewage sludge (Com-til®, City of Columbus) 3:1 mix (by vol). At transplant, the seedlings were top dressed with 15N-7P-12K Osmocote (Scotts Miracle-Gro, Co., Marysville, Ohio) at 181.6g (0.4 lbs) of fertilizer per container. Plants were hand watered twice daily as needed until the study commenced on June 6, 2005. Stem caliper was taken 15 cm (6 in) above the substrate surface. Plant height was measured from the substrate surface to the shoot tip.

Total pore space, air-filled and water-filled pore space was determined gravimetrically for the substrate using 54.4 L (14 gal) containers. Five single container replications were used. Each container was lined with a plastic bag, placed on a balanced and tared. The container was filled to within 2.5 cm (1 in) of the rim with water, the water height marked on the container and the weight recorded, which yielded the container volume. The container was emptied, filled with air-dried substrate to the volume mark, tared and then the substrate was saturated with water and allowed to equilibrate. The weight of water added represented an approximation of the total pore space of the substrate. Holes were then made in the plastic liner and the substrate allowed to for drain for one hour, after which the weight was recorded. The difference in the drained weight and the air-dried weight represents an approximation of the water filled pore space at field capacity. The difference in weight between the saturated and drained weights represents an approximation of the air-filled pore space at field capacity. The weights were converted to percent values by dividing by container volume and multiplying by 100.

EXPERIMENTAL PROCEDURES

Irrigation was delivered by one Spot Spitter (Roberts Irrigation, CA, model SS-AG 160 LGN) per container which, provided approximately 450 ml (0.12 gal) water min^{-1}. The seedlings were randomly assigned to one of four treatment groups each consisting of two replications with five plants per replication. Each replication had one indicator plant and four constituent plants. The irrigation treatments were: 1) one scheduled irrigation event at 16:30 hours daily for 15 min (a predicted irrigation volume of 6.75 L day^{-1} [1.8 gal. day^{-1}]); 2) 100% of effective container capacity (ECC); 3) 80% of ECC; and 4) 60% of ECC. In this study, ECC represents the maximum mass of the container, substrate, and seedling after gravitational water has drained. Thus, ECC represents the weight of the container-substrate-plant unit plus the weight of the total substrate water holing capacity one hour after termination of an irrigation event.

On June 6, 2005 ECC for each of the indicator plants was determined by monitoring gravimetric changes at one-second intervals while all forty seedlings were irrigated. Gravimetric changes were obtained by placing each indicator plant on a balance connected to a computer. A macro written in Visual Basic for Applications (VBA) allowed the individual weights of the eight indicator plants to be collected and logged simultaneously into a spreadsheet. Irrigation was continued until the gravimetric changes held constant for twenty seconds, which we considered the effective saturation weight (ESW). Once ESW was reached, irrigation was discontinued and while the media drained gravimetric changes were monitored every second for the next hour or until a constant weight was obtained. The combined mass of the plant, container and substrate after one hour (or until a constant weight was obtained) was used as ECC and as the baseline or target weight for determining the initiation and termination of subsequent irrigation events.

A second macro written in VBA monitored all eight indicator plants throughout the study and logged their weights every 30 minutes. At each 30 minute interval, if the weight of an indicator plant was less than 9 g (0.02 lbs) of its target weight, the solenoid controlling that indicator plant and the other four "crop" plants within the replication was opened and remained open until the target ECC weight was recorded. When the target weight was reached, the solenoid was turned off. The accuracy of the balance was ± 9 g (0.02 lbs), thus we chose a 9 g weight difference to trigger an irrigation event. Plant water use over a given time interval was determined by summing the irrigation volumes (as weights) for that period.

The ECC value may change during a production cycle due to plant growth, root growth into air-filled pore space, and decomposition of the organic fraction of the substrate. Therefore, ECC for each indicator plant was re-calculated on July 9 and August 8 during the season by using the procedure described above.

Monthly, stem calipers and plant heights were measured as described earlier. At the completion of the study all forty trees were harvested. All substrate was washed from the roots. Trees were then separated into roots and aerial parts (stems and leaves) and placed in a drying oven at 68 C (155 F) until a constant weight was obtained. Dry weights for each tree's parts were recorded. Dried root and aerial tissues of individual plant parts were ground to pass through a 2 mm (0.08 in) screen and 5g (0.18 oz) sub-samples sent to the STAR Lab at the Ohio Agriculture and Research Development Center for macro-nutrition analysis (http://www.oardc.ohio-state.edu/starlab/). Total plant nitrogen (N), phosphorus (P), and potassium (K) content was determined by multiplying the N, P, K concentrations of each sub-sample by their respective dry weights and summing individual plant's root and aerial nutrient contents.

The data were analyzed using the one-way ANOVA procedure within SPSS (SPSS, Inc., Chicago, IL). Means were separated using the Student-Newman-Keuls test at $\alpha = 0.05$ level of significance.

RESULTS AND DISCUSSION

Components of the irrigation monitoring system worked reliably under outdoor conditions. No maintenance was required during the four-month experimental period other than to re-boot the computer once following an electrical storm.

Substrate in the 54.4 L (14 gal) containers averaged 46% total pore space. Air-filled and water-filled pore spaces were 18 and 28%, respectively. Initial ECC values averaged 26.65 kg (58.7 lb) on June 6 for the indicator plants. Effective container capacity weights were determined on two additional dates to correct for possible changes in ECC. There were no differences between treatment groups for ECC values measured on July 9 (26.29 kg or 57.8 lb) or August 8 (27.33 kg or 60.2 lb). Under the conditions of this experiment, there was little change in ECC during the experimental period.

On June 6 initial plant heights and calipers averaged 131 cm (52 in) and 14.2 mm (0.6 in), respectively (Table 2.1 and 2.2). There were no differences in plant height or caliper until August 13 (Table 2.1 and 2.2). From June 6 through July 22 the plants grew 9 cm (3.5 in) in height and 1.5 mm (0.06 in.) in caliper (Table 2.1 and 2.2). On August 13 and September 6 plant caliper in the 60% ECC treatment group was less than those in the 80% ECC, 100% ECC, and scheduled irrigation treatment groups (Table 2.2). Heights on August 13 and September 6 were similar for plants under the 60 and 80% ECC treatments and these were less than heights of those in the 100% ECC and scheduled irrigation treatments (Table 2.1).

Root, shoot and total plant dry weights of plants under the 100% ECC and scheduled irrigation treatments were greater than those under 60 and 80% ECC (Table 2.3). Shoot/root ratios were similar for all treatments (Table 3). Total plant dry mass accumulation for plants under the 100, 80 and 60% ECC treatment groups was 97, 81 and 67%, respectively, of plants under scheduled irrigation.

Growing plants under the irrigation control and monitoring system described was similar to growing plants under cyclic irrigation, but with more frequent irrigation cycles of lower volume. In other cyclic irrigation studies, plant growth or quality was greater than under a single daily irrigation event (Beeson and Haydu, 1995, Beeson and Keller, 2003, Beeson, 1992, Keever and Cobb, 1985, Tyler et al., 1996, Warren and Bilderback, 2002). In contrast, there was no difference in baldcypress growth between once daily schedule irrigation and 100% ECC (cyclic) treatments. The lack of difference in plant size between once daily scheduled irrigation and 100% ECC treatments may be due to the relatively small-sized plants grown in large-sized containers used in this study compared with other studies. The 54.5 L containers had 28% water-filled pore space and contained an estimated 15.2 L (4.0 gal) of water. The maximum water use for the plants under scheduled irrigation was 2.8 L (0.7 gal) on August 17 (Table 2.4). Thus, even with one irrigation event per day it is unlikely that the plants were water stressed.

Leachate electrical conductivity was not measured in this study because no leachate occurred in the 100, 80 and 60% ECC treatments. Under non-leaching irrigation treatments, substrate soluble salts would build up unless leached by rain events. In August and September, rainfall was 13 cm (5.0 in) and 9 cm (3.5 in) above average, respectively (Table 2.6). Thus, rainfall likely reduced the soluble salt levels in the 60, 80, and 100% ECC treatment groups and positively affected plant growth.

There were no differences in daily water use on the dates measured among plants in the four irrigation treatments on July 8; average daily water use was 1087 g (2.8 gal), Table 2.4). On July 24 and August 17, plants under the 100% ECC and scheduled irrigation treatments used more water per day than those under the 80 and 60% ECC treatments (Table 2.4). Plants under 100% ECC and scheduled irrigation had 65% higher water use than those under 60 and 80% ECC treatments on August 17. These dates were chosen because no rain occurred on the day of water use determination and for the two previous days and represent the only three day rainless periods during the 2005 growing season.

Water use was equal to irrigation volume for plants under the 60, 80 and 100% ECC treatments (Table 2.4). Therefore, irrigation application efficiency in these treatment groups was 100% (no leaching attributed to irrigation events). Plants under scheduled irrigation received an average of 6.75 L (1.72 gal) of water day^{-1} throughout the study. Plant water use under scheduled irrigation was similar to that of plants under the 100% ECC treatment. Because irrigation volume was delivered in excess of plant demand, water use efficiencies were 17, 33 and 42% on July 8, July 24, and August 17, respectively for scheduled irrigation. Daily irrigation demand ranged from 1.1 L (0.29 gal) in July to 2.7 L (0.71 gal) in August.

Plants in 100% ECC and scheduled treatments accumulated similar amounts of N, P, and K, but higher amounts than plants under the 60 and 80% ECC treatments (Table 2.5) because of greater dry mass; irrigation treatment had no effect on tissue nutrient concentrations (Table 2.5). Published foliar N concentration (1.79%, Mills and Jones, 1996) were similar to the whole plant tissue N concentrations found in this study. However, foliar P (0.14%) and K (0.44 to 0.51%) levels were approximately half of those reported in Table 2.5.

Mineral nutrients are leached when irrigation volume exceeds container capacity (Thomas and Perry, 1980). Thus, it is likely that fertilizer rates could be reduced under highly efficient irrigation application systems. Lower fertilizer rates would also reduce EC values in low leachate production systems.

The plant-integrated irrigation monitoring and control system described can be used to reduce leachate under diverse (with respect to taxa, substrate, container geometry, irrigation application devices, or diverse climatic conditions) container production systems. Under the system described, only the weight of the container-substrate-plant unit at ECC needs to be determined, as that weight represents the practical maximum water holding capacity for that unit. Monitoring weight changes to manage irrigation volume is easier, and less expensive, that using dielectric moisture sensors (Nemiali and van Iersel, 2002) or modeling (Bauerle et al., 2002). The method described here does not require sophisticated software, or technical expertise to operate. The system operated under outdoor conditions with minimal maintenance and within a similar range of substrate moisture content as described for a dielectric monitoring system (Nemiali and van Iersel, 2002).

Our study showed that substrate moisture content can be monitored gravimetrically to significantly reduce leaching and irrigation volume without compromising plant quality when baldcypress is irrigated at 100% ECC. Future research is needed to investigate the effects of reduced leaching fraction on plant growth in other production systems.

Treatment [y]	Height (cm) June 6	July 22	August 13	September 6
100% CC	127a [z]	137a	155a	167a
80% CC	128a	138a	144b	156b
60% CC	132a	139a	140b	154b
Scheduled	135a	145a	161a	170a

Table 2.1. Baldcypress height for four dates during a growing season. Plants were grown in trade 54.4 L containers under different substrate moisture contents. Substrate moisture treatments were initiated in June.

[y] Scheduled irrigation plants received 6.75 L per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[z] Means within a column followed by different letters are different ($\alpha = 0.05$) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

	Caliper (mm)			
Treatment [y]	June 6	July 22	August 13	September 6
100% CC	13.6a [z]	15.2a	19.4a	25.1a
80% CC	14.5a	15.8a	19.6a	22.2a
60% CC	14.8a	15.1a	16.6b	20.8b
Scheduled	14.2a	15.9a	19.9a	25.2a

Table 2.2. Baldcypress caliper for four dates during a growing season. Plants were grown in trade 54.4 L containers under different substrate moisture contents. Substrate moisture treatments were initiated in June.

[y] Scheduled irrigation plants received 6.75 L per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[z] Means within a column followed by different letters are different (α =0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

	Dry mass (g)			
Treatment[y]	Roots	Shoots	Total plant	Shoot-to-root ratio
100% ECC	203.5a[z]	318.0a	521.3a	1.6a
80% ECC	171.7b	265.0b	436.7b	1.5a
60% ECC	149.5b	211.0b	360.5c	1.4a
Scheduled	202.9a	334.9a	537.8a	1.7a

Table 2.3. September baldcypress dry mass after plants were grown under different substrate moisture contents in trade 54.4 L containers for one growing season. Substrate moisture treatments were initiated in June.

[y] Scheduled irrigation plants received 6.75 L per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[z] Means within a column followed by different letters are different (α =0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

	Water use (ml per 24 hours)		
Treatment[y]	July 8	July 24	August 17
100% CC	1080.0a[z]	2250.0a	2632.5a
80% CC	1102.5a	1408.5b	1766.3b
60% CC	1061.1a	1170.0b	1732.5b
Scheduled	1102.5a	2153.3a	2767.5a

Table 2.4. Baldcypress plant daily water use for three dates during a growing season. Plants were grown in trade 54.4 L containers. Substrate moisture treatments were initiated in June.

[y] Scheduled irrigation plants received 6.75 L per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[z] Means within a column followed by different letters are different (α =0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

Treatment [y]	Total plant (g) N	P	K	Total pant concentration (%) N	P	K
100% CC	9.26a [z]	1.56a	6.11a	1.78a	0.29a	1.17a
80% CC	7.72b	1.12b	5.03b	1.77a	0.26a	1.15a
60% CC	6.23c	0.88b	4.00c	1.73a	0.24a	1.11a
Scheduled	9.25a	1.57a	6.67a	1.72a	0.29a	1.24a

Table 2.5. Whole plant mineral nutrient content and nutrient concentration of baldcypress plants in September after growing under four substrate moisture levels.

[y] Scheduled irrigation plants received 6.75 L per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[z] Means within a column followed by different letters are different (α =0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

	Rainfall (cm)	
Month	Actual	Average[1]
June	10.0	10.3
July	10.7	11.7
August	22.8	9.5
September	16.3	7.4

Table 2.6. Actual and average monthly rainfall amounts for June to September, Columbus, Ohio.

[1]30 year average for Columumbs, OH obtained from http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/nrmlprcp.html

CHAPTER 3

THE EFFECTS OF NEAR-ZERO LEACHATE IRRIGATION ON GROWTH AND WATER AND NUTRIENT EFFICIENCIES OF CONTAINER GROWN BALDCYPRESS (*Taxodium distichium*L.) SEEDLINGS

ABSTRACT

Improving water- and nutrient use-efficiencies in container nurseries requires an understanding of the interaction of various irrigation fertilization practices. Fertilizer effectiveness relies on adequate substrate moisture; as substrate moisture is reduced so is the effectiveness of the fertilizer application. Because the most common fertilizers used in container nursery production are inorganic (inorganic fertilizers are chemically considered salts) low substrate moisture can result in soluble salt damage to plant roots; the damage can be described as osmotic dehydration. However, as irrigation volume is increased the leaching of nutrients from the container substrate is increased, resulting in lowered water- and nutrient use efficiencies. This study was conducted to determine if gravimetric monitoring of a plant-substrate-container unit could be used to manage irrigation volume on a real-time basis and the effect on irrigation and leachate

volume, nutrient- and water-use efficiency, and baldcypress (*Taxodium distichium* L.) growth.

The study results showed that a near-zero leachate irrigation system will decrease irrigation volume and (by definition) decrease leachate volumes, increase the fertilizer concentration of the substrate resulting in increased plant tissue nutrient concentration, and increase water-use efficinecy. Nutrient-use efficiency was not affected by irrigation regime in this study, as fertilizer rate impacted uptake of nitrogen. Baldcypress growth was reduced under the near-zero leachate irrigation regime, presumably due to soluble salt damage.

INTRODUCTION

For container-grown plants the rooting volume is limited, compared to the rooting volume available to a field grown plants. This limited rooting volume can be quickly depleted of moisture and nutrients by a rapidly growing plant. To combat this problem growers must supply the substrate daily with suitable moisture and nutrients. With the typical soil-less, porous, substrates used in container production the result has been the inefficient use of irrigation and nutrients due to excessive leaching.

Fertilizer effectiveness relies on adequate substrate moisture; as substrate moisture is reduced so is the effectiveness of the fertilizer application (Squire et al., 1987). Because the most common fertilizers used in container nursery production are inorganic (inorganic fertilizers are chemically considered salts) low substrate moisture can result in soluble salt damage to plant roots; the damage can be described as osmotic dehydration. However, as irrigation volume is increased the leaching of nutrients from the container substrate is increased (Warren and Bilderback, 2005). Groves et al. (1998) showed that substrate nitrogen concentrations decreased as irrigation volume increased with a CRF fertilizer, this result was due to excessive leaching. Controlled release fertilizers (CRF) have been used to reduce leaching of available N; leached N with CRF has been reported between 12 and 29% (Tyler, 1996a). Improving irrigation and nutrient use efficiencies (NUE) in container nurseries requires an understanding of the interaction of various irrigation and fertilizer practices. To maximize NUE, fertilizer release rate should match plant uptake potential. Until plant nutrient uptake patterns are better understood, the best way to improve NUE is through refining irrigation rate and delivery techniques (Struve, 1995).

Irrigation scheduling refers to how much irrigation to apply and when to apply the irrigation (Warren and Bilderback, 2005; Warren and Bilderback, 2004). An effective strategy for scheduling irrigation is to measure how much water the plants are using and then replace that amount, this strategy would be defined as precision irrigation. Several studies have examined various methods and recommendations for estimating irrigation amounts and are summarized in Sammons and Struve (2008).

Best management practices (BMPs) recommend the use of a 0.2 leachate fraction (LF) to guide irrigation volumes (Yeager, et al., 1997). LF is calculated by the volume of irrigation leached ÷ volume of irrigation applied (Warren and Bilderback, 2005).

The LF recommendation centers on managing the accumulation of soluble salts in the substrate to maintain electrical conductivity (EC) levels below those that damage plant roots. Tyler et al. (1996b) showed that a low LF reduced irrigation volume, leachate volume and leached N by 44%, 63% and 66%, respectively, compared to a high

LF, but with a 10% reduction in plant growth. But because woody plant production involves the use of CRF and outdoor production with plentiful rainfall, managing the LF may not be needed (Warren and Bilderback, 2005). In fact, the use of high LF can deplete CRF materials within 100 days of application (Ruter, 1992; Yeager et al. 1993; Yeager and Wright, 1982). The use of an elevated LF results in a decrease of water application efficiency (WAE) and nutrient use efficiency (NUE). The use of LF does not effectively address, how much irrigation and when to apply.

Accumulation of soluble salts under near-zero leachate irrigation is a concern. For instance, Tyler et al. (1996a) showed that fertilizer release rates exceed that of plant uptake for the two rates tested. This suggests fertilizer rate could be reduced without consequence to plant growth. By matching fertilizer rate to plant uptake potential, plant injury to soluble salts could be reduced, even under near-zero leachate fractions.

The objective of this study was to determine if gravimetric monitoring of a plant-substrate-container unit could be used to manage irrigation volume on a real-time basis and to study the effect of a near-zero leachate irrigation system on baldcypress (*Taxodium distichium* L.) growth, water use, and nutrient uptake. The hypothesis was that under near-zero leachate irrigation: irrigation and leachate volume would be decreased; fertilizer concentration of the substrate would be increased; water use and nutrient uptake efficiency would be increased; and at standard or normal fertilizer rates plant growth would be decreased due to high soluble salt levels (high EC); while at ½ the standard or normal fertilizer rate, plant growth would not be effected as soluble salts would not reach damaging levels.

MATERIALS AND METHODS

PREPARATION OF PLANT MATERIAL

In the summer of 2006, 400 baldcypress seedlings (from Wilmington College, Wilmington, Ohio) were transplanted into #1 Spinout®-treated (Griffin Corp.,Valdasta, GA) plastic containers (Classic 400, Nursery Supplies, Fairless Hills, PA) at the Howlett Hall greenhouses located on the Columbus campus of The Ohio State University. The substrate was Fafard 3B (Conrad Fafard, Inc. Agawam, MA). Seedlings were maintained weed free and watered twice daily with 100 ppm of 21N-2.9P-4.3K (21-7-7 Peters, Scotts Miracle-Gro Co., Marysville, OH) water-soluble fertilizer until September 1. After September 1 the seedlings were only watered as needed. The seedlings were over-wintered in an unheated poly-house until the spring of 2007.

One hundred and eighty eight baldcypress seedlings, selected for uniformity (height and caliper), were transplanted to #3 containers (11.4 l, 27.9 cm top diameter, 24.1 cm tall, Classsic 1200 Nursery Supplies, Fairless Hills, PA) on May 1, 2007 and placed pot to pot on a gravel production pad within a retractable roof structure (RRS) (Cravo Equipment, Ltd., Brantford, Ontario, Canada) on the Columbus campus. The roof of the RRS remained closed for the duration of the study to eliminate rainfall, side walls were opened when temperatures exceded 23.8 C (75 F) and closed when the temperature was below 23.8 C (75 F). The substrate was a 3:1 mix (by volume) pine bark, composted municipal sewage sludge (Com-til®, City of Columbus).   Plants were hand watered twice daily as needed until the study commenced on May 24, 2007.

EXPERIMENTAL PROCEDURES

On May 24, initial stem caliper, plant height measurements and initial destructive harvests were performed. Stem caliper was taken 15 cm (6 in) above the substrate surface. Plant height was measured from the substrate surface to the shoot tip. All substrate was washed from the roots of three randomly selected seedlings. The seedlings were then separated into roots and aerial parts (stems and leaves) and placed in a drying oven at 68 C (155 F) until a constant weight was obtained. Dry weights for each seedling's parts were recorded. Dried root and aerial tissues of individual plant parts were ground to pass through a 2 mm (0.08 in) screen and 5g (0.18 oz) sub-samples sent to the STAR Lab at the Ohio Agriculture and Research Development Center for macro-nutrition analysis (http://www.oardc.ohio-state.edu/starlab/). Total plant nitrogen (N), phosphorus (P), and potassium (K) content was determined by multiplying the N, P, K concentrations of each sub-sample by their respective dry weights and summing individual plant's root and aerial nutrient contents.

Total pore space, air-filled and water-filled pore space was determined gravimetrically for the substrate using #3 containers. Five single container replications were used. Each container was lined with a plastic bag, placed on a balance and tared. The container was filled to within 2.5 cm (1 in) of the rim with water, the water height marked on the container and the weight recorded which yielded the container volume. The container was emptied, filled with air-dried substrate to the volume mark, tared and the substrate saturated with water and allowed to equilibrate. The weight of water added represented an approximation of the total pore space of the substrate. Holes were then made in the plastic liner and the substrate allowed to for drain for one hour, after which the weight was recorded. The difference in the drained weight and the air-dried weight represents an approximation of the water filled pore space at field capacity. The difference in weight between the saturated and drained weights represents an approximation of the air-filled pore space at field capacity. The weights were converted to percent values by dividing by container volume and multiplying by 100.

The remaining seedlings were randomly assigned to one of four treatment groups. The treatments were a factorial combination of two fertilizer rates and two irrigation regimes. The two fertilizer treatments were 45g or 90g of 15N-3.1P-12.5K (15-7-15 Multicote, 4-month controlled release fertilizer). The 45 and 90 gram treatments are equivalent to 0.49 or 98 Kg N m^{-3} (1 or 2 lb. N $yard^{-3}$), respectively. The fertilizer for each container was placed into an ankle length panty hose packet, each packet containing 45 g of the fertilizer. The packets were placed on the substrate surface near the center of the container and under the irrigation stream. This method of fertilizer application was used to facilitate end-of-experiment CRF collection in order to analyze the amount of N remaining within the prills. This fertilizer application method approximated a top-dress application method. The two irrigation treatments were daily irrigation events at 0730 and 1230 hours to maintain a weekly 0.20 leachate fraction or a near-zero leachate fraction maintained by a plant integrated computer-controlled irrigation monitoring system (Sammons and Struve, 2008). Regardless of the irrigation treatment, all irrigation was delivered by one Spot Spitter (Roberts Irrigation, CA, model SS-AG 160 LGN) per container which provided approximately 450 ml (0.12 gal) water min^{-1}. For the 0.2 LF, irrigation volume was adjusted weekly to account for plant growth.

The near-zero leachate fraction treatments used one indicator plant per treatment to determine irrigation volumes based on the container-substrate-plant-substrate moisture weight, termed the effective container capacity (ECC). The ECC weight represents the combined weight of the container-substrate-plant unit plus the weight of the water held after the gravitational water has drained.

The ECC weight for each of the indicator plants (one per treatment group) was determined by monitoring gravimetric changes at one-second intervals while simultaneously irrigating all of the “crop” seedlings. Gravimetric changes were obtained by placing each indicator plant on a balance connected to a computer. A macro written in Visual Basic for Applications (VBA) allowed the individual weights of the eight indicator plants to be collected and logged simultaneously into a spreadsheet. Irrigation was continued until the gravimetric changes held constant for twenty seconds, which we considered the effective saturation weight (ESW). Once ESW was reached, irrigation was discontinued and while the substrate drained, gravimetric changes were monitored every second for the next hour or until a constant weight was obtained. The combined mass of the plant, container and substrate after one hour (or until a constant weight was obtained) was used as ECC set weight for determining the initiation and termination of subsequent irrigation events.

To maintain the ECC set weight a second macro written in VBA monitored each indicator plant throughout the study and logged their weights every 3 hours. At each 3 hour interval, if the weight of an indicator plant was less than its target weight, the solenoid controlling that indicator plant and the other “crop” plants within the treatment group was opened and remained open until the target ECC “set” weight was recorded.

When the “set” weight was reached, the solenoid was turned off. Plant water use over a given time interval was determined by summing the irrigation volumes (as weights) for that period. To account for possible changes in ECC “set” weights due to plant growth, root growth into air-filled pore space, and decomposition of the organic fraction of the substrate, new ECC set weights for each indicator plant were re-calculated monthly during the season.

EXPERIMENT 1

Eighty-four uniform plants were grouped into one of four irrigation zones (0.3 m within and 0.6 m between row spacing), each zone represented a single irrigation-fertilizer treatment combination, with 21 single plant replications. The plants were arranged on the gravel production pad under a retractable roof structure (RRS).

At three week intervals three randomly selected plants from each treatment were destructively harvested to obtain dry weights and mineral nutrient contents, as described earlier. These plants were used to develop incremental dry mass accumulation, and nutrient uptake curves. Each curve was fitted with linear or quadratic equations where $P \leq 0.05$ significance level using SigmaPlot for Windows® (Systat Software, Inc., San Jose, CA)

EXPERIMENT 2

This experiment had five, five plant replications per treatment arranged in a randomized complete block design (RCBD). The treatments were a factorial combination of two fertilizer rates (45 g and 90 g) and two irrigation regimes (0.20 leachate fraction and ECC based near-zero leachate), as previously described. The plants were placed on 1 m (3 ft) high benches constructed from dimensional lumber and covered with galvanized steel fencing (Fig 1). A leachate collection system (LCS) was constructed to collect leachate from each . The LCS consisted of 24 acrylic troughs, one hung under each plot. The troughs were positioned with a gradual slope to funnel leachate to 24 five-gallon collection buckets, one per plot. The acrylic troughs were formed from sheets of acrylic by heating them with a blow torch followed by manually forming a lip that funneled the leachate into a bucket.

Monthly, stem calipers and plant heights were measured as described earlier. Leachate volume, pH, EC, and total NO_3- concentration were measured weekly. Leachate from each plot was measured to yield a total volume of leachate for each replication. Leachate pH, EC, and NO_3-N content were measured at weekly intervals using cardi meters (Horiba Instruments, Inc, Irvine CA). Total leachate NO_3-N contents were determined by multiplying the NO_3-N concentrations of each sub-sample by their respective total leachate volume. Cumulative leached NO_3-N was determined for each treatment group by summing their respective weekly NO_3-N leachate contents.

At the end of the growing season seedlings from the LCS were destructively harvested to obtain root and shoot dry weights and whole plant mineral nutrient measurements as described earlier. For each treatment total whole plant nutrient (nitrogen [N], phosphorous [P], and postassium [K]) content and concentration, nitrogen uptake efficiency (NUE), and water use efficiency (WUE) were calculated. Total whole plant nutrient accumulation was calculated as: $[N_e - N_b]$, where N_e is the end of season nutrient content and N_b is the initial nutrient content. NUE was calculated as: $[(N_e - N_b)/N_t]$, where N_e is the end of season N content, N_b is the initial N content, and N_t is the total N applied from CRF. WUE was calculated as: $[(PDW_e - PDW_b)/I_t]$, where PDW_e is the end of season whole plant dry weight, PDW_b is the baseline whole plant dry weight, and I_t is the total irrigation volume applied to individual containers across the growing season.

RESULTS AND DISCUSSION

The 3:1 pinebark:Com-til® (by volume) substrate in the 11.4 liter (3gal) containers averaged total pore, air- filled pore, and water-filled pore space of 50, 32, and 18%, respectively. Initial ECC values were 6.8kg (15 lb) 0 days after initiation (DAI) for both the 90g CRF & ECC and 45g CRF & ECC treatment groups. ECC values were calibrated at 45 and 81 DAI; at 45 DAI the ECC target was adjusted to 7.0kg (15.5 lb) and remained at this value following the calibration occurring at 81 DAI. The total irrigation applied to the 90g and ECC, 45g and ECC, 90g and 0.2 LF, and the 45g and 0.2 LF treatment groups during the experiment was 106.3, 93.6, 208 and 208 liters, respectively.

Over the course of the study nitrogen (N) release from the CRF fertilizer was best described by a quadratic equation (Fig. 3.2.). Du et al. (2006) and Shaviv et al. (2003) describe nutrient release from a CRF as being sigmoidal and occurring in three separate phases (lag, steady release, and decay). The CRF used had a six month release profile, while the duration of the study (114 days) was less than four months. Therefore, the quadratic equation describing release of N (Fig. 3.2) accounts for the lag and steady release phases described by Du et al. (2006) and Shaviv et al. (2006). At 114 DAI the CRF had released 48.5% of its N content (Fig. 3.2).

Leachate EC spiked between 15 and 29 DAI for all four treatment groups. During this time frame EC was at or above recommended EC value (0.8 ds m^{-1}) for container production of woody plants fertilized with CRF (Yeager, et al., 1997). The spike in EC supports the finding that CRF fertilizers may exhibit a “front end dumping” of nutients, probably due to mechanical imperfection of the prills resulting from the manufacturing process or damage during shipping. Leachate pH values are inversely related to EC values for all four treatment groups (Fig. 3.3).

Incremental stem height and caliper. For all four treatment groups curves for incremental stem height and caliper were best described by linear and quadratic equations, respectively (Fig. 3.5 & 3.6). The equations suggest height growth of baldcypress remains constant across the growing season, while caliper growth of baldcypress increased through the September harvest date. Initial stem height averaged 30 cm and stem caliper averaged six mm. Stem height and caliper increased for the 90g CRF and ECC, 45g CRF and ECC, 90g CRF and 0.2 LF, and 45g CRF and 0.2 LF treatment groups at 16, 33, 51, 82 and 114 DAI are summarized in (Fig. 3.5 and 3.6). Incremental height growth was the least at 33 DAI for all four treatment groups (Fig.3.5). This lag in height growth may be a result of high EC values of the substrate preceding this measurement (Fig. 3.2); there was a return to “normal” growth in plant height of baldcypres after EC values lowered.

Whole plant dry mass accumulation. Whole plant dry mass accumulation was best described by quadratic equations for all four treatment groups (Fig. 3.7). Initial whole plant dry mass averaged 97g per plant (Fig. 3.7), with 53.6% of the total plant dry mass contained in the shoots (Table 3.1) and a root-to-shoot ratio of 0.86 (data not shown).

From 0 DAI through 114 DAI the 90g CRF and 0.2 LF treatment group accumulated the most dry mass (222.8g per plant) while the 45g CRF and ECC accumulated the least dry mass (129g per plant) (Fig. 3.7). Whole plant dry mass accumulation for all treatment combinations at 23, 49, 79, and 114 DAI is presented in Figure 3.7. For all of the treatment groups, the greatest increase in growth occurred between 79 and 114 DAI, except for the 45g CRF and ECC treatment group (Fig. 3.7). The fraction of whole plant dry mass contained in the shoots decreased for each treatment group over the duration of the experiment (Table 3.1). The root-to-shoot ratios for the 90g CRF and ECC, 45g CRF and ECC, 90g CRF and 0.2 LF, and 45g CRF and 0.2 LF treatment groups at 23, 49, 79 and 114 DAI were: 1.1, 1.2, 1.5, and 1.5; 1.1, 1.2, 1.4, and 1.5; 1.1, 1.1, 1.4, and 1.4; 1.1, 1.3, 1.4, and 1.2, respectively.

Whole plant nitrogen uptake. Whole plant N uptake was best described by quadratic equations for all treatment groups except the 45g CRF and ECC treatment group, which was best described by a linear equation (Fig. 3.8). N uptake in baldcypress is highly correlated with dry mass accumulation, this result is consistent with N uptake of other species (Larimer and Struve, 2002). Initial whole plant N content averaged 2.8 g N (Fig. 3.8) with 78.9% of the total N contained in the shoots (Table 3.2). The 90g CRF and ECC (4.11g N) and 90g 0.2 LF (4.76g N) treatment groups accumulated on average 150% more N per plant than the 45g CRF and ECC (2.67g N) and 45g CRF and 0.2 LF (3.04g N) treatment groups (Fig.3.7). The fraction of whole plant N content contained in the shoots decreased drastically from 0 to 23 DAI for all treatment groups (Table 3.2). This result suggests the root N content was depleted to support intial bud break and growth flush, once the plants began to photosynthesize the roots were able to increase N concentration to support later root growth. The fraction of whole plant N content contained in the shoots (Table 3.2) relative to the percent of whole plant dry mass contained in the shoots (Table 3.1) at 49, 79 and 114 DAI suggest that the N concentration of baldcypress roots increases throughout the growing season. Whole plant N uptake for each treatment combination at 23, 49, 79 and 114 DAI is presented in Figure 3.8.

Whole plant phosphorous uptake. Whole plant P uptake was best described by linear equations for all treatment groups, this suggests that P uptake in baldcypress occurs at a constant rate across the growing season (Fig. 3.9). Initial whole plant P content averaged 0.26g (Fig. 3.8) and the fraction of whole plant P content contained in the shoots was 71.1% (Table 3.3). The fraction of whole plant P content contained in the shoots was drastically reduced, about 45% on average, from 0 to 23 DAI (Table 3.3), similar to the pattern of N concentration of root and shoot tissues (Table 3.2) displayed over the same time period. Thereafter, it remained relatively constant for the remainder of the growing season. Whole plant P uptake for each treatment combination at 23, 49, 79 and 114 DAI is presented in Figure 3.9.

Whole plant potassium uptake. Whole plant K uptake was best described by linear equations for all treatment combinations, this suggests that K uptake in baldcypress occurs at a constant rate across the growing season (Fig. 3.10). Initial whole plant K content averaged 0.82g (Fig. 3.10) and the fraction of whole plant K content contained in the shoots was 87.8% (Table 3.4). The fraction of whole plant K content contained in the shoots was drastically reduced from 0 to 23 DAI (Table 3.4), similar to the pattern of both N and P concentration of root and shoot tissues (Table 3.2 & 3.3) displayed over the same time period. Whole plant K accumulation for each treatment combination at 23, 49, 79 and 114 DAI is presented in Figure 10.

End-of-season dry weight. There were no significant fertilizer by irrigation interactions for root and whole plant dry weight, or root-to-shoot ratio (Table 3.5). There was a significant fertilizer by irrigation interaction for shoot dry weight (Table 3.5). For the ECC irrigation regime shoot dry weight was reduced by 19% when fertilized with 45g CRF compared to 90g CRF. This result was not expected based on the higher EC values of the 90g CRF and ECC compared to 45g CRF and ECC (Fig.3.3). However, the irrigation volume applied to the 45g CRF and ECC may have been underestimated by the indicator plant; the whole plant dry weight of the 45g CRF and ECC indicator plant was 20% less (data not shown) than the average whole plant dry mass of its constituents at the end of season (Table 3.5). The ECC irrigation regime reduced both root and whole plant dry weight by 14% compared to the 0.2 LF irrigation regime. There were no statistical differences in end of season root-to-shoot ratios (Table 3.5).

End-of-season nutrient content and concentration. There were significant fertilizer by irrigation interactions for whole plant N, P, and K content and whole plant P and K concentration (Table 3.6). For the ECC irrigation regime whole plant N, P, and K content was reduced by 25, 26, and 42% when fertilized with 45g compared to 90g CRF (Table 3.6). The 90g CRF and ECC treatment group had the greatest whole plant N, P, and K content and concentration (Table 3.6). This supports the hypothesis that substrate fertilizer concentration is increased under near-zero irrigation (ECC). The two groups receiving the 0.2 LF irrigation regimes had similar N, P, and K tissue contents and concentrations (Table 3.6), showing the addition of excess fertilizer under this irrigation system is of no benefit to plant performance.

Water-use and nitrogen uptake efficiency. There was no significant fertilizer by irrigation interaction (Table 3.7). There was a main effect of irrigation on WUE of baldcypress; the ECC irrigation regime was 175% more efficient than the 0.2 LF irrigation regime (Table 3.7). There was a main effect of fertilizer on NUE; the 45g CRF rate was 147% more efficient than the 90g CRF rate. NUE values reported in table 3.7 were affected by the presence of Comtil® in the substrate, as this potting amendment provided a significant nutrient contribution. These results support our hypothesis that near-zero leachate irrigation does increase WUE, however irrigation regime did not effect NUE.

Conclusions. This study showed that a near-zero leachate irrigation system will decrease irrigation volume and (by definition) decrease leachate volumes, increase the fertilizer concentration of the substrate resulting in increased plant tissue nutrient concentration, and increase WUE. NUE was not affected by irrigation regime in this study, as fertilizer rate impacted uptake of nitrogen.

The EC values encountered during the first 40 DAI for the treatment groups receiving the ECC irrigation regime were extremely high and well above recommended substrate EC levels (Yeager et al, 1997). Baldcypress did exhibit reduced growth in response to the elevated EC levels, however there was no plant mortality. More salt sensitive species may be more negatively effected by this trend in EC under a near-zero leachate irrigation system. This irrigation method may require weekly leaching events in the during the first 5weeks of production to eliminate the accumulation of excessive soluble salts.

Under the 0.2 LF irrigation regime the results suggest that the use of 90g compared to 45g of fertilizer is of no benefit to plant performance.

This study was performed under a closed roof of a RRS that occluded the addition of rainfall as an additional source of irrigation. Warren and Bilderback (2005) suggest that the use of LF may not be needed in production regions with plentiful rainfall. Further research is needed to evaluate these two irrigation regimes and fertilizer rates with the inclusion of rainfall.

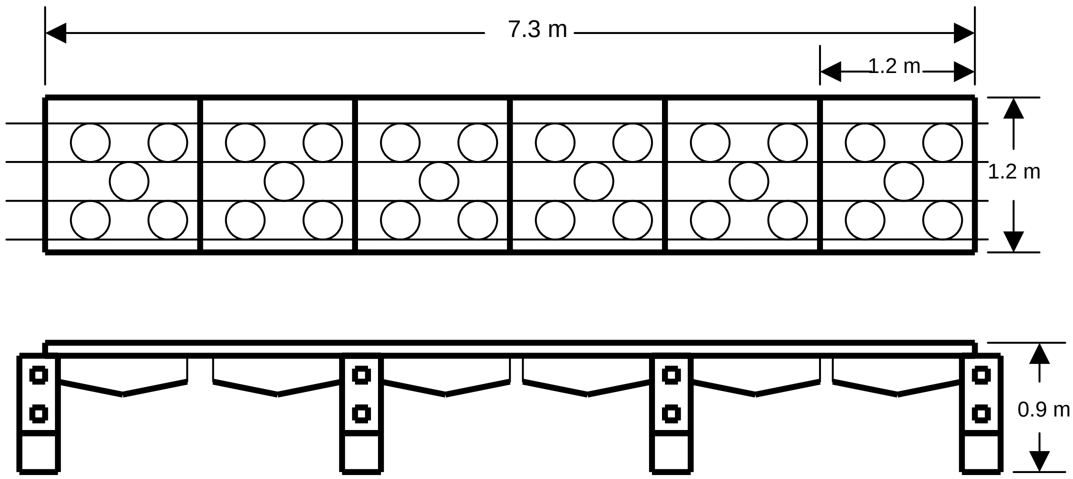

Figure 3.1. Leachate Collection System (LCS). The LCS was constructed from dimensional lumber, galvanized steel fencing was used for the bench top to allow leachate to be collected. A 0.9 m square sheet of acrylic was hung under each plot to capture leachate. The acrylic was shaped to funnel leachate into a five gallon bucket. The benches were set on cinder blocks and irrigation lines ran across the bench tops.

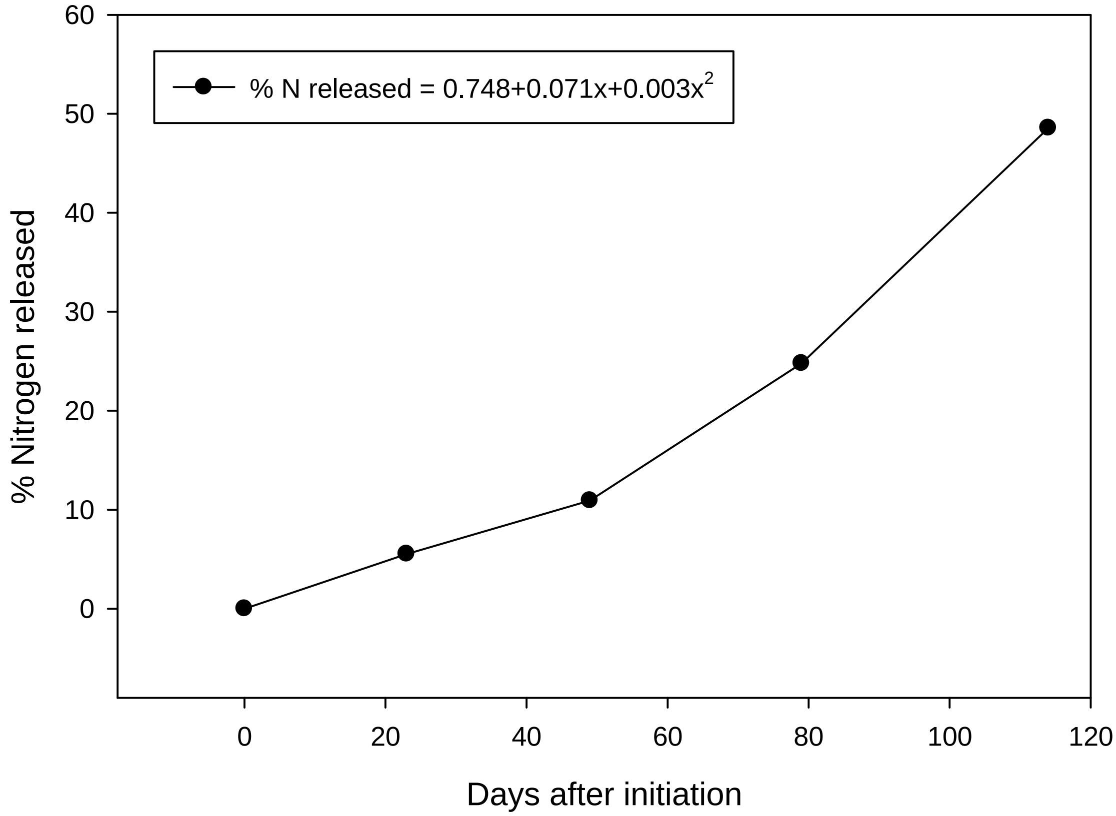

Figure 3.2. Release of Nitrogen from CRF (15-7-15 Multicoat 6 month formulation) CRG placed in mesh bags and placed on the substrate surface. The bags were harvested and analysed for total nitrogen during the growing season. Each point is mean of 12 replications; $R^2 \geq 0.998$.

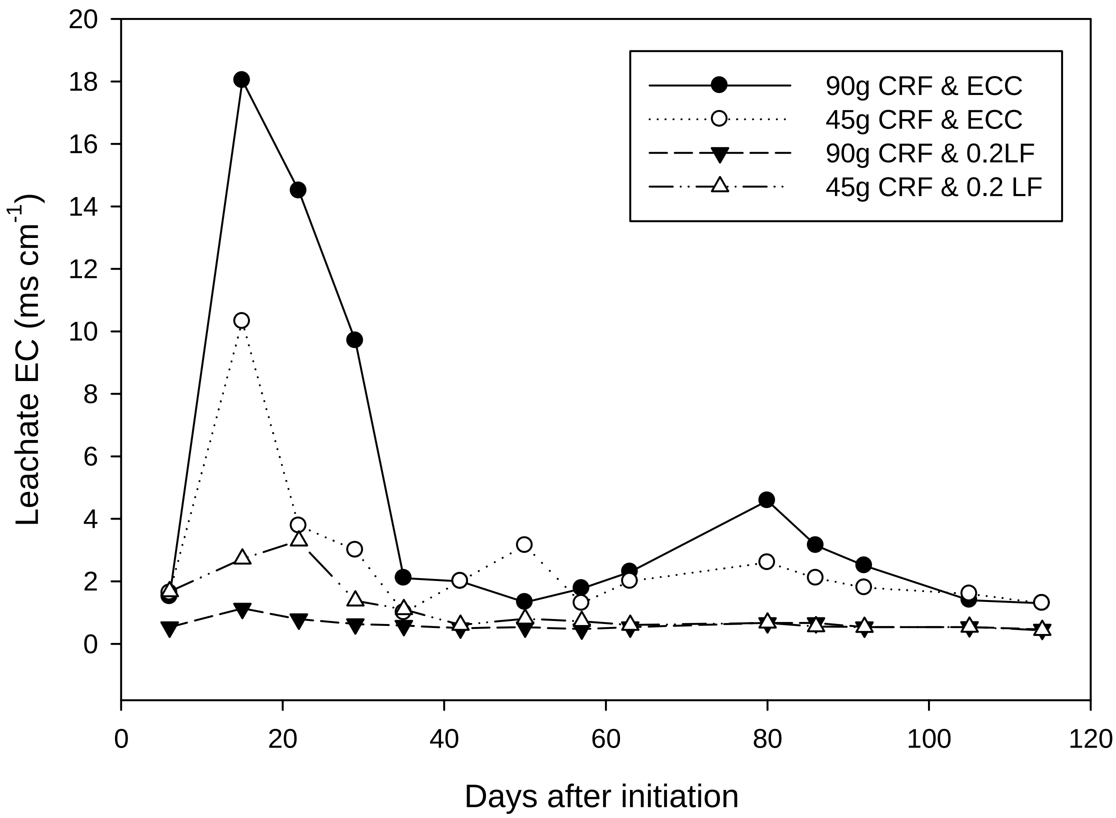

Figure 3.3. Container leachate electrical conductivity (EC) of baldcypress plants grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each point is the mean of five, five plant replications.

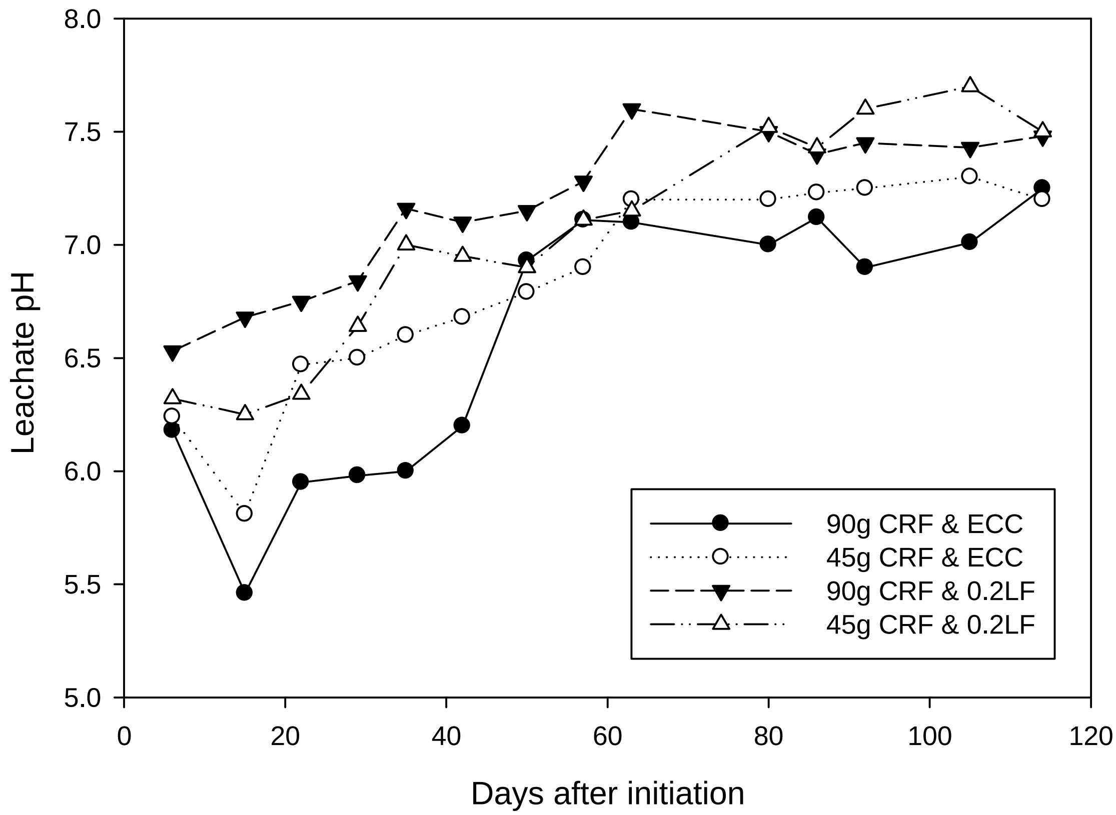

Figure 3.4. Container leachate pH of baldcypress plants grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each point is the mean of five, five plant replications.

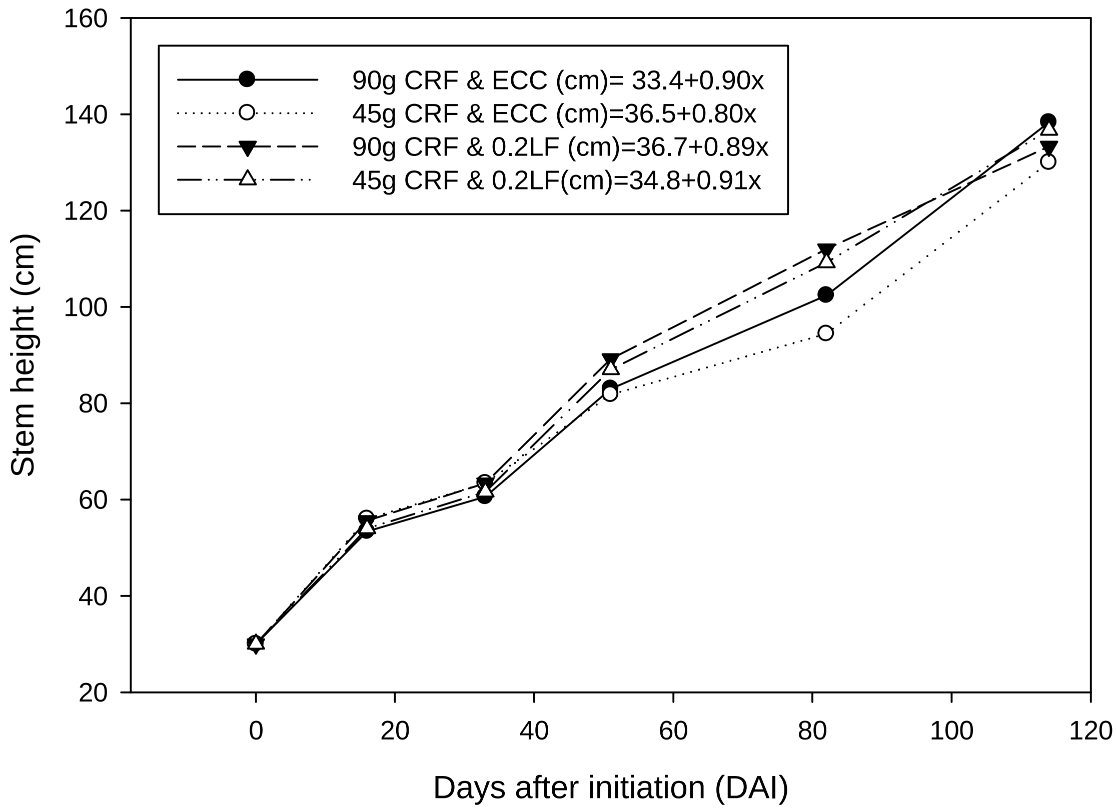

Figure 3.5. Stem height measurements of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 25 plants per treatment combination; $R^2 \geq 0.971$ for all four equations presented.

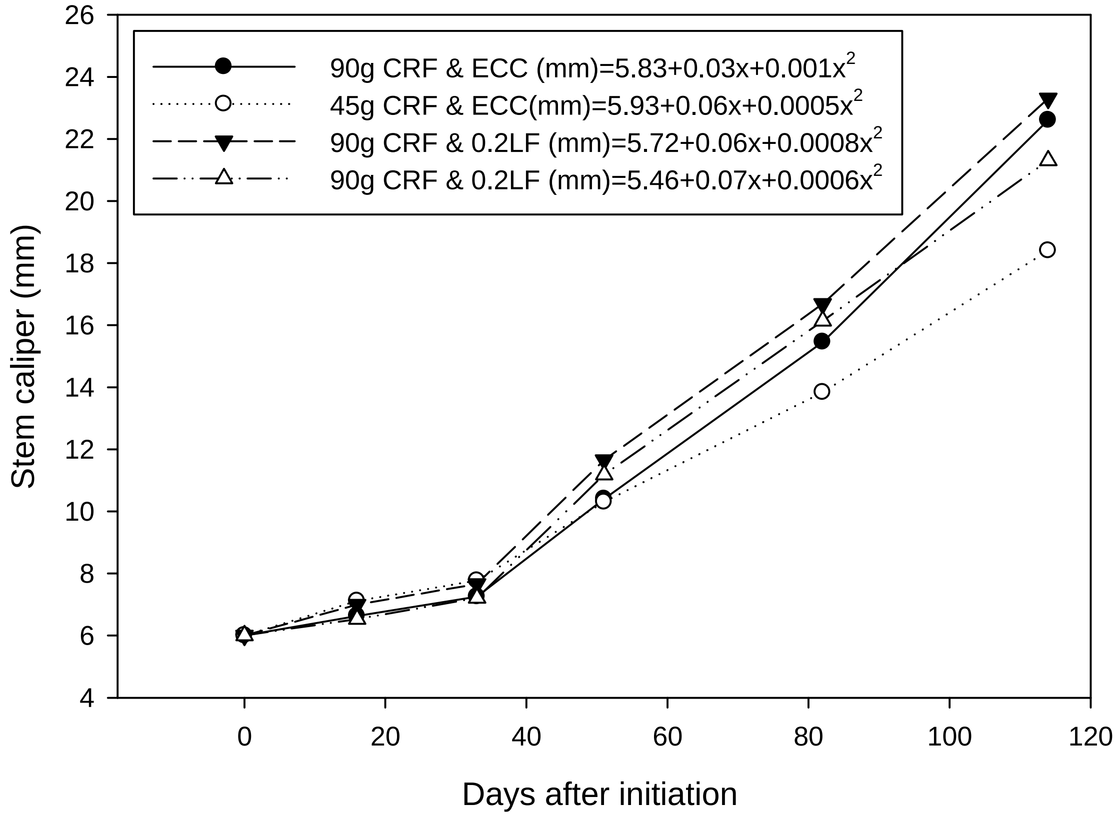

Figure 3.6. Stem caliper measurements of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 25 plants per treatment combination; $R^2 \geq 0.986$ for all four equations presented.

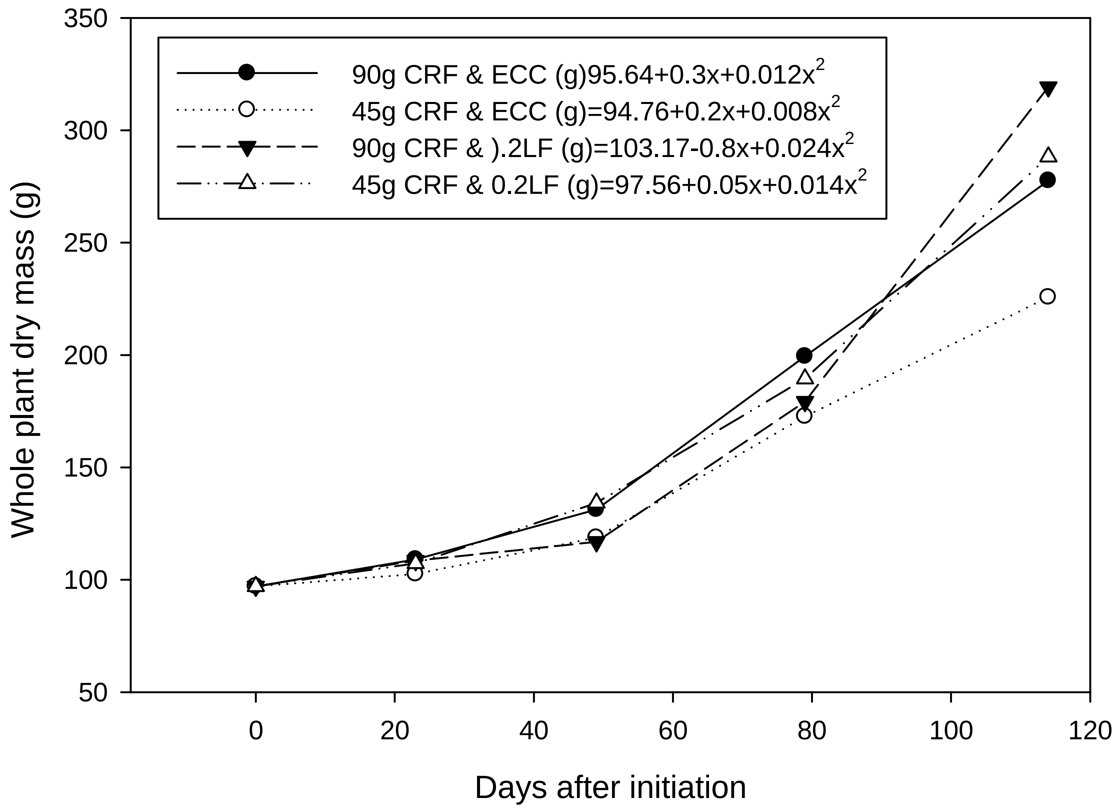

Figure 3.7. Whole plant dry mass accumulation of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 3 plants per treatment combination; $R^2 \geq 0.989$ for all four equations presented.

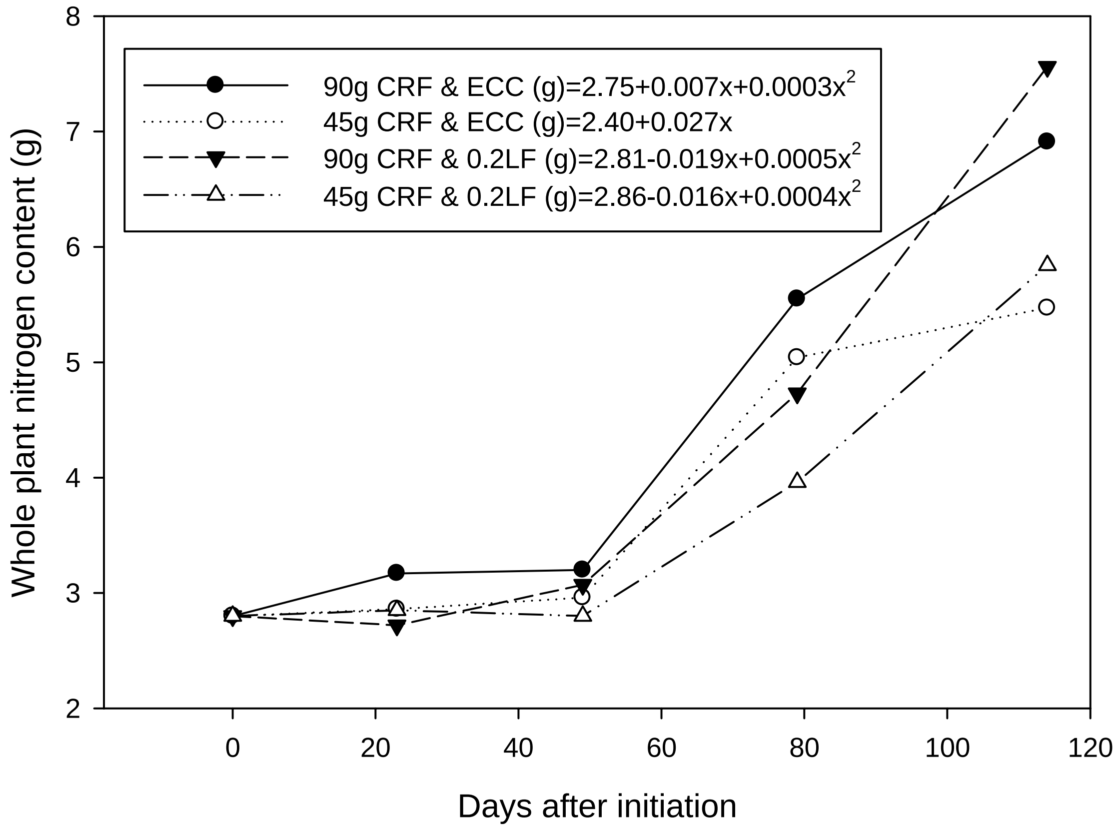

Figure 3.8. Whole plant nitrogen content accumulation of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 3 plants per treatment combination; $R^2 \geq 0.951$ for all equations except 45 g CRF & ECC which was 0.851.

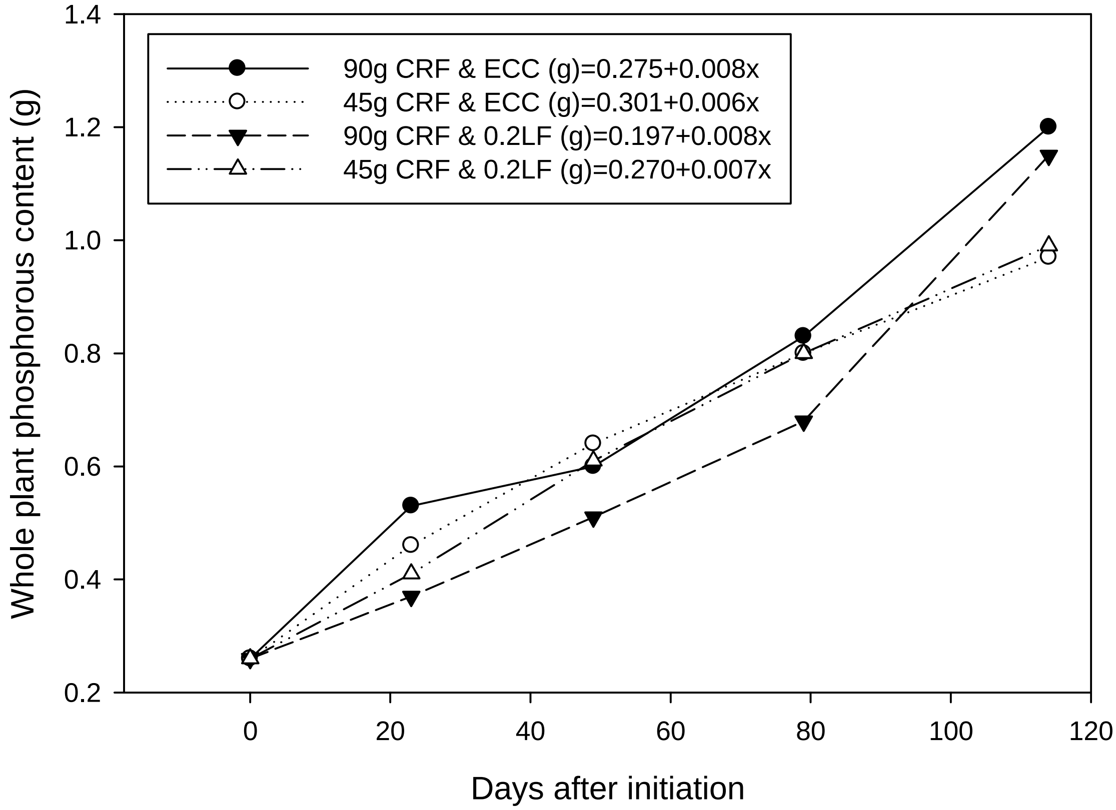

Figure 3.9. Whole plant phosphorous content accumulation of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 3 plants per treatment combination; $R^2 \geq 0.941$ for all four equations presented.

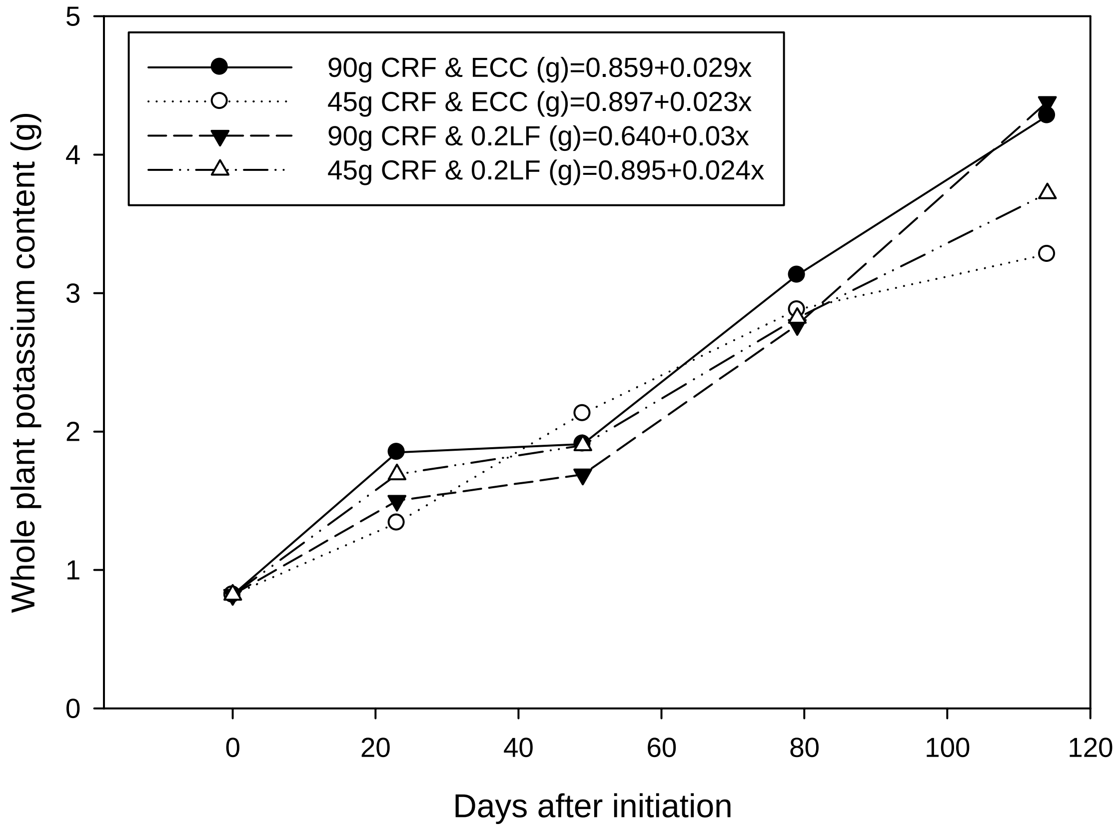

Figure 3.10. Whole plant potassium content accumulation of baldcypress seedlings grown under two CRF rates (90g or 45g 15-7-15 Multicoat 6 month formulation) and two irrigation regimes (effective container capacity [ECC] or 0.2 leachate fraction [LF]) for 114 days. Each value is the mean of 3 plants per treatment combination; $R^2 \geq 0.949$ for all four equations presented.

Treatment	Dry mass (g)				
	0DAI	23DAI	49DAI	79DAI	114DAI
90g CRF & ECC	53.6	50.0	44.6	40.2	39.9
45g CRF & ECC	53.6	48.6	46.0	42.3	40.4
90g CRF & 0.2 LF	53.6	47.3	47.3	41.6	41.4
45g CRF & 0.2 LF	53.6	47.7	43.0	42.2	45.1

Table 3.1. The ratio of shoot to whole plant dry mass of baldcypress seedlings for 114 days.
Each value is the mean of three plants per treatment combination.

	Percent nitrogen content				
Treatment	0DAI	23DAI	49DAI	79DAI	114DAI
90g CRF & ECC	78.9	43.2	37.8	35.1	34.0
45g CRF & ECC	78.9	45.8	42.9	35.5	35.3
90g CRF & 0.2 LF	78.9	42.3	38.4	35.7	34.1
45g CRF & 0.2 LF	78.9	44.2	30.4	34.3	34.1

Table 3.2. The percentage of shoot to whole plant nitrogen content of baldcypress seedlings grown for 114 days.
Each value is the mean of three plants per treatment combination.

	Percent phosphorous content				
Treatment	0DAI	23DAI	49DAI	79DAI	114DAI
90g CRF & ECC	71.1	49.1	53.3	49.4	35.8
45g CRF & ECC	71.1	47.8	52.3	43.8	42.3
90g CRF & 0.2 LF	71.1	54.0	51.0	47.1	45.2
45g CRF & 0.2 LF	71.1	46.3	45.9	56.2	49.2

Table 3.3. The percentage of shoot to whole plant phosphorous content of baldcypress seedlings grown for 114 days.
Each value is the mean of three plants per treatment combination.

Treatment	Percent potassium content				
	0DAI	23DAI	49DAI	79DAI	114DAI
90g CRF & ECC	87.8	57.8	49.7	46.0	42.1
45g CRF & ECC	87.8	53.0	53.0	51.0	41.2
90g CRF & 0.2 LF	87.8	60.0	48.5	50.2	41.3
45g CRF & 0.2 LF	87.8	55.6	47.9	55.7	46.5

Table 3.4. The percentage of shoot to whole plant potassium content of baldcypress seedlings grown for 114 days.l
Each value is the mean of three plants per treatment combination.

Fertilizer Rate[w]	Irrigation Regime[x]	Dry Mass (g) Roots	Shoots	Whole Plant	Root-to-Shoot Ratio
90g	ECC	193.6[y]	165.3	358.8	1.2
45g	ECC	180.6	133.6	314.2	1.3
90g	0.2 LF	220.0	172.0	391.9	1.3
90g	0.2 LF	217.5	172.9	390.3	1.3
Fertilizer		NS[z]	**	NS	NS
Irrigation		***	***	**	NS
Fertilizer x Irrigation		NS	**	NS	NS

Table 3.5. Root, shoot and whole plant dry mass and root-to-shoot ratio of baldcypress plants grown for 114 days under two fertility levels and two irrigation regimes.

[w] plants were fertilized with 90g or 45g of controlled release fertilizer (CRF) of 15-7-15 Multicoat 6 month formulation.

[x]Plants were irrigated using a effective container capacity [ECC] or a 0.2 leachate fraction [LF] to determine irrigation volumes.

[y]Each value is the mean of 25 plants.

[z] *, **, *** indicate significance at 0.05, 0.01 and 0.001 level, respectively, using ANOVA. NS indicates no statistical difference at $\alpha = 0.05$.

Fertilizer Rate[w]	Irrigation Regime[x]	Total plant (g) N	P	K	Total plant concentration (%) N	P	K
90 g	ECC	7.41[y]	1.39	0.12	2.08	0.39	0.03
45 g	ECC	5.56	1.03	0.07	1.76	0.33	0.02
90g	0.2 LF	6.72	1.00	0.08	1.71	0.26	0.02
45g	0.2 LF	6.14	1.16	0.08	1.60	0.30	0.02
Fertilizer		***[z]	NS	***	**	NS	***
Irrigation		NS	*	**	***	***	***
Fertilizer x Irrigation		*	***	**	NS	**	**

Table 3.6. Whole plant mineral nutrient content and nutrient concentration of baldcypress plants grown for 114 days under two fertility levels and two irrigation regimes.

[w] plants were fertilized with 90g or 45g of controlled release fertilizer (CRF) of 15-7-15 Multicoat 6 month formulation.

[x]Plants were irrigated using a effective container capacity (ECC)or a 0.2 leachate fraction (LF) to determine irrigation volumes.

[y]Each value is the mean of 25 plants.

[z] *, **, *** indicate significance at 0.05, 0.01 and 0.001 level, respectively, using ANOVA. NS indicates no statistical difference at $\alpha = 0.05$.

Fertilizer Rate[w]	Irrigation Regime[x]	Water-use efficiency (g/L)	Nitrogen uptake efficiency
90 g	ECC	3.38	70.4
45 g	ECC	3.36	89.8
90g	0.2 LF	1.88	59.8
45g	0.2 LF	1.97	101.1
Fertilizer		NS[z]	***
Irrigation		***	NS
Fertilizer x Irrigation		NS	NS

Table 3.7. Water-use efficiency and nitrogen uptake efficiency baldcypress plants grown for 114 days under two fertility levels and two irrigation regime.

[w] plants were fertilized with 90g or 45g of controlled release fertilizer (CRF) of 15-7-15 Multicoat 6 month formulation.

[x]Plants were irrigated using a effective container capacity (ECC)or a 0.2 leachate fraction (LF) to determine irrigation volumes.

[y]Each value is the mean of 25 plants.

[z] *, **, *** indicate significance at 0.05, 0.01 and 0.001 level, respectively, using ANOVA. NS indicates no statistical difference at $\alpha = 0.05$.

CHAPTER 4

pH, EC, AND NITRATE VALUES FOR CONTAINER SUBSTRATES COMPRISED OF PINE BARK AND COM-TIL® WITH AND WITHOUT CONTROL RELEASE FERTILIZER

ABSTRACT

This study investigated the contribution of Com-til®, control release fertilizer (CRF) and a combination of the two on early substrate leachate pH, EC, and nitrate-nitrogen levels. Com-til® contributed to elevated EC values and provides significant amounts of nitrate-nitrogen during the first 21 days after planting. Under the study conditions CRF did show elevated early release of nutrients, or dumping.

INTRODUCTION

In container nurseries two types of fertilizers are used; soluble fertilizers and controlled release fertilizers (CRF). Soluble fertilizers can also be applied through fertigation, the practice of providing nutrients to plants with water soluble fertilizer injected into the irrigation water. However, this technique can be inefficient, especially if paired with over-head irrigation practices. CRFs are fertilizer products that slowly reslease their nutrient packages into the surrounding potting substrate.

Coated water-soluble fertilizers are the most common CRFs used in container nursery production. These CRFs are coated with a polymer that is the responsible for the release rate; the polymers are typically a sulfur, a polymeric substance or a combination of both (Goertz, 1993). These fertilizer types have also been called polymer-coated fertilizers or PCFs (Goertz, 1993). The polymer coating forms a semi permeable membrane that allows water vapor to diffuse into the capsule, the vapor then condenses and dissolves a portion of the soluble fertilizer, the dilute fertilizer then moves out of the membrane by diffusion or hydrostatic pressure (Goertz, 1993 and Bunt, 1988).

Du et al. (2006) and Shaviv et al. (2003) describe nutrient release from a CRF as being sigmoidal and occurring in three separate phases (lag, steady release, and decay). CRFs may provide more efficient delivery of nutrients than liquid feed; it has been estimated that ten times more nutrients are lost with liquid feed than with CRFs (Sanderson, 1987). The increase in efficiency of CRFs is due to the prolonged slower release of nutrients over the growing season.

However, nutrient release from CRFs is temperature dependent; 200% increase in nutrient release resulting form every 10 C increase in temperature (Husby et al., 2003 and Lunt and Oertli, 1962). Merhaut et al. (2006) reported that nutrient release was accelerated over the first third of the release profile, indicated by elevated electrical conductivity (EC) rates during that time frame, for all CRFs tested. Elevated EC rates under greenhouse conditions on the front end of the release profile suggest that CRF release rates may not match plant uptake potentials and lead to an increase in the leaching of nutrients from the substrate.

Recent research has investigated the effect of various substrate amendments on water and nutrient efficiencies in container production (Fitzpatrick et al., 1998 and Owen et al. 2007). The City of Columbus produces a composted municipal sewage sludge, Com-til®, that can be used as a substrate amendment for container production of woody ornamentals. Com-til® has an analysis of at least 2-1-1. Com-til® used in combination with CRF can result in high leachate EC readings (personal observation).

In this experiment we investigated the contribution of Com-til®, CRF, and a combination of the two on leachate pH, electrical conductivity (EC), and Nitrate during the early stages of CRF release.

Materials and Methods

The 21 day study was conducted in the Howlett Hall greenhouses located on the Columbus campus of The Ohio State University. The treatments were a combination of three substrates with or without CRF; a total of six treatment groups. The substrates used were 100% pine bark, 100% composted municipal sewage sludge (Com-til®, City of Columbus), or a 3:1 mix (by volume) pine bark, Com-til®. The substrates were mixed by hand and filled to within 2cm of the rim #3 containers (11.4 l, Classic 1200 Nursery Supplies, Fairless Hills, PA). The fertilizer used was a 15N-3.1P-12.5K (15-7-15 Multicote, 4-month) CRF applied to the surface of the substrate at a rate of 90g per container, which was equivalent to 0.98 Kg of N m^{-3} (2 lb. N $yard^3$). Each treatment had three individual container replications arranged in a completely randomized design and spaced pot-to-pot on a greenhouse bench. A complete randomized design was used due to small experiment footprint (about 7.32 m^2). At the beginning of the study each container was irrigated to achieve container capacity prior to the addition of CRF.

At three day intervals 250ml of irrigation was applied by hand to the substrate surface. The irrigation volume was applied as two 125ml events to promote uniform wetting of the substrate. Conatiners were placed in saucers to capture leachate volume. Leachate volume EC, pH, and nitrate nitrogen were measured at each irrigation event.

The data were analyzed using the one-way ANOVA procedure within SPSS (SPSS, Inc., Chicago, IL). Means were separated using the Student-Newman-Keuls test at $\alpha = 0.05$ level of significance.

Results and Discussion

Leachate volume average 130ml for each treatment group and "irrigation" event during the entire study (data not shown), resulting in a 0.52 leachate fraction. The average daily temperature during the study was 75 F (23.8 C) with maximum and minimum temperatures of 80 F (26.6 C) and 68 F (20 C), respectively.

Ph. Initial pH values averaged 4.9 for all treatment groups (Table 4.1). There was a increase in pH values for all treatment groups at 6 days after intiation (DAI) (Table 4.1). The treatment groups not receiving CRF had higher pH values by 15 DAI, except for the pine bark substrate with no CRF group (Table 4.1). The 100% Com-til® and Com-til:PB substrates without CRF had the highest pH (7.9) at the 21 DAI (Table 4.1). The increase in pH for substrates without CRF is a result of leaching during the experiment and is consistent with previous results (Roberts et al, 2001). The decrease in pH for substrates with CRF suggests that the continuous release of nutrients from the CRF contributes to maintaining acceptable pH, the optimal substrate pH values is 6 for container grown plants (Yeager et al, 1997).

EC. EC values for substrates with CRF increased, but decreased for substrates without CRF over the 21 days of the experiment (Table 4.2). At 21 DAI the addition of CRF increased EC values by 181%, 1466%, 400%, for the 100% Com-til®, 100% PB, and the Com-til®:PB substrates, respectively (Table 4.2). EC levels for the 100% Com-til® substrate without CRF were above 4 ms cm^{-1} from 0 to 21 DAI. When PB was amended with Com-til with no CRF applied EC values, maximum of 3 ms cm^{-1} to minimum of 1.5 ms cm^{-1}, were closer, but still above the acceptable range (0.2 to 0.8 ms cm-1) (Yeager et al., 1997) for container production (Table 4.2). The PB substrate without CRF had the lowest EC values (Table 4.2).

Nitrate nitrogen. At the start of the study the substrates containing Com-til® had 607% more nitrate nitrogen than the other two Substrates regardless of CRF (Table 4.3). For all three substrates, nitrate nitrogen decreased in the absence of CRF and increased in the presence of CRF over the 21 days of the experiment (Table 4.3). For each substrate type, at 12 DAI, nitrate-nitrogen levels were higher for substrates with CRF than without CRF (Table 4.3). The results suggest that Com-til® can contribute a significant source of nitrate-nitrogen, for at least the first 3 weeks of production.

This experiment was conducted in containers without the removal of nutrients by plants; therefore the nitrate-nitrogen and EC values reported may be higher than what would be encountered in a production environment. The results do indicate that Com-til® does contribute to high EC values and does provide a significant source of nitrate-nitrogen in the first three weeks of production, suggesting CRF application may not be needed immediately at potting. In this study, CRF release did display an accelerated rate of release or “dumping” at the front end.

Substrate[x]	Fertilizer[y]	pH 0	3	6	9	12	15	18	21
Com-til®	Yes	5.3a[z]	5.2a	7.5a	7.6a	7.6ab	7.6a	7.5a	7.6a
	No	5.2a	7.5b	7.8bc	7.5a	7.6ab	7.8b	7.8b	7.9b
PB	Yes	4.7a	6.7b	7.7b	7.7a	7.5a	7.5a	7.6a	7.6a
	No	3.6a	7.8b	7.9c	7.7a	7.7ab	7.7ab	7.7ab	7.8b
Com-til:PB	Yes	5.3a	5.3a	7.6b	7.7a	7.5a	7.5a	7.6a	7.5a
	No	5.3a	7.6b	8.1d	7.6a	7.8b	7.9b	7.8b	7.9b

Table 4.1. Leachate pH for three substrates with or without CRF at 0, 3, 6, 9, 12, 15, 18 and 21 days after initiation.

[x]The substrates were 100% composted municipal sewage sludge (Com-til®, City of Columbus), 100% pine bark (PB), or a 3:1 mix (by volume) PB, Com-til®.

[y]90g of controlled release fertilizer (15-7-15, Mulicote, 6month).

[z]Means within a column followed by different letters are different ($\alpha = 0.05$) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 3 containers.

		EC (ms cm^{-1})							
Substrate[x]	Fertilizer[y]	0	3	6	9	12	15	18	21
Com-til®	Yes	6.8a[z]	7.5a	7.5a	6.9a	7.8a	7.7a	7.9a	8.0a
	No	5.8a	6.1ab	5.6b	4.7b	4.7b	4.6b	4.3b	4.4b
PB	Yes	1.4b	1.8d	2.8c	3.6b	4.4b	4.5b	4.4b	4.4b
	No	2.0b	0.4d	0.7d	0.5c	0.4c	0.4c	0.3c	0.3c
Com-til:PB	Yes	2.5b	4.3bc	3.6c	4.6b	5.6b	5.7b	5.8b	6.0b
	No	3.0b	2.5cd	3.3c	1.9c	1.9c	1.8c	1.7c	1.5c

Table 4.2. Leachate EC for three substrates with or without CRF at 0, 3, 6, 9, 12, 15, 18 and 21 days after initiation.

[x]The substrates were 100% composted municipal sewage sludge (Com-til®, City of Columbus), 100% pine bark (PB), or a 3:1 mix (by volume) PB, Com-til®.

[y]90g of controlled release fertilizer (15-7-15, Mulicote, 6month).

[z]Means within a column followed by different letters are different ($\alpha = 0.05$) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 3 containers.

		N-nitrate nitrogen (ppm)							
Substrate[x]	Fertilizer[y]	0	3	6	9	12	15	18	21
Com-til®	Yes	866a[z]	1019a	1134a	927a	920a	950a	996a	1065a
	No	713a	766b	736b	613b	490b	467b	437b	398b
PB	Yes	91b	184cd	329cd	383bc	375b	391b	383b	383b
	No	26b	13d	24d	21d	6c	4c	3c	2c
Com-til:PB	Yes	182b	368c	406c	544c	552b	582b	598b	613b
	No	221b	264cd	246cd	178cd	121c	108c	95c	75c

Table 4.3. Leachate N-nitrate nitrogen for three substrates with or without CRF at 0, 3, 6, 9, 12, 15, 18 and 21 days after initiation.

[x]The substrates were 100% composted municipal sewage sludge (Com-til®, City of Columbus), 100% pine bark (PB), or a 3:1 mix (by volume) PB, Com-til®.

[y]90g of controlled release fertilizer (15-7-15, Mulicote, 6month).

[z]Means within a column followed by different letters are different ($\alpha = 0.05$) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 3 containers.

CHAPTER 5

CONCLUSION

Improving irrigation and nutrient efficiencies in container nurseries requires and understanding of the interactions of various irrigation and fertilizer practices, as well as, the effect of container substrate characteristics. The results of these studies highlight important interactions that should be considered when developing a fertilization and irrigation requirements for container grown crops.

Current Best Management Practices (BMP) suggest nursery producers should irrigate container grown crops using a 0.2 leachate fraction (LF) to mediate the accumulation of soluble salts in the container substrate (Yeager et al., 1997). Accumulation of soluble salts in the substrate can retard plant growth by osmotic dehydration of root tissue. Warren and Bilderback (2005) presented a consenting opinion by hypothesizing that the use of a LF may not be required in regions where rainfall is plentiful and fertilizer application rates more closely match plant uptake potentials. Excessive EC rates, greater than 0.8 ms cm^{-1} for control released fertilizers (CRF) (Yeager et al., 1997), can retard growth of baldcypress, as seen in the study performed during the summer of 2007 (Chapter 3) when rainfall was occluded by a retractable roof structure (RRS). However, in the study performed during the summer 2005 (Chapter 2) the 100% ECC treatment group did not experience a reduction growth relative to the control treatment, suggesting that the addition of rainfall can effectively remove the accumulated salts from the container substrate, in central Ohio. Future work should focus on near-zero irrigation with reduced fertilization in presence of rainfall to determine acceptable fertilizer application rates.

The best way to increase nutrient use efficiencies is to match fertilizer nutrient release rate to plant uptake potential. Season long nutrient uptake of baldcypress showed nitrogen accumulation was best described by a quadratic equation (Fig. 3.8), while phosphorous and potassium accumulation was best described by a liner equations (Fig. 3.9 and 3.10). Nutrient release form CRF are best described by a sigmoidal equation with all nutrients being released uniformly, except phosphorous which is released slower due to lower solubility (Du et al., 2006 and Shaviv et al., 2003). In baldcypress, only nitrogen plant uptake matches CRF release, while the release of phosphorous and potassium is greater than plant uptake of those nutrients. A better understanding of plant nutrient uptake potentials of woody plants needs to be understood to maximize nutrient-use efficiencies.

Substrate amendment can be used to increase water holding and nutrient holding capacity of the typically coarse, porous substrates used in container production of woody ornamentals. The use of Com-til® as a substrate amendment provides a significant amount of nitrogen and does elevate substrate leachate EC values. The results suggests that CRF application may not be needed during the first three weeks of production when Com-til® is used and an amendment. Because Com-til® does increase substrate leachate values, it may be of benefit to regularly wet stock piles to prevent excessive salt accumulation. Further investigation of potting mix amendments to improve the water-holding capacity and nutrient retention properties of container substrates is needed.

It may be of benefit to leach containers during the first two to three weeks of production to remove soluble salts caused by “front end dumping” of some CRF products. Accelerated release of CRF nutrient contents or “front end dumping” was confirmed in two studies (Chapter 3 and 4) and has been documented by other researchers (Merhaut et al., 2006). “Front end dumping” may result from mechanical damge of the prill coating that allows the nutrient contents to be release, or by a greater contribution of hydrostatic pressure, as opposed to diffusion, on the influence of nutrient movement outside of the prill coating when the prill is completely filled with nutrients.

The plant-integrated irrigation system used and described can be used to effectively reduce leachate volumes and deliver desirable leachate fractions in container production. The system we describe does not require sophisticated software or technical expertise to operate. The system operated outdoors reliably and with minimal maintenance. While there is commercial application for this plant-integrated irrigation system, the ability to monitor and maintain container substrate moisture within narrow and precise intervals would also be useful for research applications.

REFERENCES

Abraham, N., P. S. Hema, E. K. Saritha, S. Subramannian. 2000. Irrigation based on soil electrical conductivity and leaf temperature. Agricultural Water Management. 45:145-157.

Altland, J. 2006. Container no-brainer. Digger, November, 2006.

American National Standards Institute, 1996. American standards for nursery stock. Amer. Assn. Nurserymen, Washington, D.C.

Bauerle, W.L., C.J. Post, M.F. Mcleod, J.B. Dudley, J.E. Toler, 2002. Measurement and modeling of the transpiration of a temperate red maple container nursery. Agric. For. Meteorol. 114:45-57.

Beeson R.C., and G.W. Knox. 1991. Analysis of efficiency of overhead irrigation in container production. HortScience 26(7):848-850.

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

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

Beeson, R. C., and K. Keller. 2003, Effect of cyclic irrigation on growth of magnoloias produced using five in-ground systems. J. Environ. Hort. 21:148-152.

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

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

Bunt, A.C. 1988. Media and Mixes for Container-Grown Plants. Unwin Hyman, London.

Devitt, D. A., M. Berkowitz, P. J. Schulte, R. L. Morris. 1993. Estimating Transpiration for three woody ornamental tree species using stem-flow gauges and lysimetry. HortScience. 28:320-322.

Du, C., J. Zhou, A. Shaviv. 2006. Release characteristics of nutrients from polymer-coated compound controlled release fertilizers. J. Polym. Environ. 14: 223-230.

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

Fitzpatrick, G.R., E.R. Duke, and K.A. Klock-Moore. 1998. Use of compost products for ornamental crop production: research and grower experience. HortScience 33:941-944.

Fonteno, W. C. 1989. An approach to modeling air and water status of horticultural substrates. Acta Horticulture. 238:67-74.

Foster, W.J., R.D. Wright, M.M. Alley, and T.H. Yeager. 1983. Ammonium absorption on a pine-bark growing medium. J Amer. Soc. Hort. Sci. 108:548-551.

Furuta, T. 1973. New Irrigation system speeds water to entire nursery. Amer. Nurseryman. 21(13):93-100.

Furuta, Tokuji. 1976. Environmental plant production and marketing. Cox Publ., Arcadia Calif.

Gilliam, C.H., R.D. Wright. 1978. Timing of fertilizer application in relation to growth flushes of 'Helleri' holly (Ilex crenata thumb.). HortScience. 13(3):300-301.

Goertz, H.M. 1993. Controlled Release Technology, p. 251-274. in: Kirk-Othmer Encyclopedia of Chemical Technology. Vol. 7. 4th ed. John Wiley, New York.

Gonzalez, R.A., D.K. Struve, L.C. Brown. 1992. A computer controlled drip irrigation system for container plant production. HortTechnology 2(3):402-407.

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

Hansen, R.C., J.C. Christman, D.A. Herms. 2006. The effects of fertility, VWC targets, choice of VWC sensors and pH modification on biomass production of poplar trees. Paper Number: 06-4133. Presented at the 2006 ASAE Annual International Meeting, Portland, Oregon July 9-12.

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

Husby, C.E., A.X. Niemiera, J.R. Harris, and R.D. Wright. 2003. Influence of diurnal temperature on nutrient release patterns of three polymer coated fertilizers. HortScience 38:387-389.

Irmak, S., D. Z. Haman, T. H. Yeager and C. Larsen. 2001. Seasonal irrigation water use efficiency of Multi-Pot Box system. J. Environ. Hort. 19:4-10.

Israelsen, O. W. and V. E. Hansen. 1962. Irrigation principles and practices. John Wiley and Sons, New York.

Kahn, S.A., R.L. Mulvaney, and C.S. Mulvaney. 1997. Accelerated diffusion methods for inorganic-nitrogen analysis of soil extracts and water. Soil Sci. Soc. Am. J. 61:936-942.

Keever, G. J., and G. S. Cobb. 1985. Irrigation scheduling effects on container media and canopy temperatures and growth of ‘Hershey’s Red’ azalea. HortScience. 20:921-923.

Lamack, W.F., A.X. Niemiera. 1993. Application method affects water application efficiency of spray stake irrigated containers. HortScience. 28(6):625-627.

Landis, T.D., Mineral nutrients and fertilization. In: Landis, T.D., Tinus, R.W. , McDonald, S.E., Barnett, J.P. (Eds.), The Container Tree Nursery Manual, vol. 4, Agricultural Handbook No. 674. USDA Forest Service, pp. 1-70.

Larimer, J. and D.K. Struve. 2002. Growth, dry weight, and nutrient distribution of red oak and “autumn flame” red maple under different fertility levels. J. Environ. Hort. 20:28-35

Lunt, O.R. and J.JOertli. 1962. Controlled release of fertilizer minerals by incapsulating membranes: II. Efficiency of recovery, influence of soil moisture, mode of application, and other ocnsidearations related to use. Soil Sci. Soc. Amer. Proc. 26:584-587.

Malik, V., Victor, R.T., 1995. Interaction of nutrient-loaded black spruce seedlings with neighboring vegetation in greenhouse environments. Can.J. For. Res. 25:1017–1023.

Mathers, H.M., T.H. Yeager, L.T. Case. 2005. Improving Irrigation water use in container nurseries. 15(1):8-12.

Merhaut, D.J., E.K.Blythe, J.P.Newman, J.P. Albano. 2006. Nutrient release from controlled-rlease fertilizers in acid substrate in a greenhouse environment: I. Leachate electrical conductivity, pH, and nitrogen, phosphorus, and potassium concentrations. Hortscience 41(3):780-787.

Mills, H. A. and J. B. Jones, Jr. 1996. Plant Analysis Handbook II. MicroMacro Publ., Inc. Athens, GA.

Morianna, A., and E. Fereres. 2002. Plant indicators for scheduling irrigation of young olive trees. Irrig. Sci. 21:81-93.

Nemiali, K. S. and M. W. van Iersel, 2002. An automated system for controlling drough stress and irrigation in potted plants. Scientia Horticulturae. 110:292-297.

Owen , J.S., S.L. Warren, T.E. Bilderback, J.P. Albano, 2007. Industrial mineral aggregate amendment affects physical and chemical properties of pine bark substrates.

Regan, R. 1997. Grouping Container Grown Plants by Water Use. Digger 41(6):24-27.

Regan, R. 1999. Nursery Irrigation Scheduling, p.1-8. Proc. 2nd Annu. Nursery Growers Short Course. Wilsonville, Ore.

Riviere, L.M., G. Chasseriaux. 1999. Different ways of monitoring the irrigation of container and pot plants. Acta Hort. 481:353-360.

Roberts, B.R., H.F. Decker, L.M. Ganahl, E.Yarmack. 2001. Biosolid residues as soilless media for growing creeping bentgrass sod. Horttechnology 11(3):451-455.

Rose, M.A., B. Biernacka. 1999. Seasonal patterns of nutrient and dry weight accumulation in freeman maple. HortSci. 34: 91-95.

Ruter, J.M. 1998. Pot-in-pot production and cyclic irrigation influence growth and irrigation efficiency of ‘Okame’ cherries. J. Environ. Hort. 16:159-162.

Ruter, J.M. 1992. Leachate nutrient content and growth of two hollies as influenced by controlled release fertilizers. J. Environ. Hort. 10:162-166.

Sammons, J.D., D.K. Struve, 2008. Monitorring of effective container capacity: a method for reducing over-irrgation in container production systems. J. Environ. Hort. 26(1):19-23.

Sakuratani, T. 1981. A heat balance method for measuring flow in the stem of intact plant. J. Agric. Meterology 37:9-17.

Sanderson, K.C. 1987. Selecting the right fertilizers for container-grown woody ornamentals. American Nurseryman. 165(1): 160-181.

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

Shaviv, A., S. Raban, E. Zaidel. 2003a. Modeling Controlled Nutrient Release from polymer coated fertilizers: diffusion release from single granules. Environ. Sci. Technol. 2251-2256.

Sneed, R. 1996. Pumps Pipes and consultations. Amer. Nurseryman. June: 45-53.

Squire, R.D., P.M. Attiwill, T.F. Neals. 1987 Effects of changes of available water and nutrients on growth, root development, and water use in Pinus radiate seedlings. Australian Forest Research 17:99-111.

Struve, D.K. 1995. Nitrogen, phosphorus and potassium recovery of container grown red oak and blackgum seedlings under different fertilizer application methods. J. Environ. Hort. 13: 169-175.

Thomas, S. and F.B. Perry. 1980. Ammonium nitrogen accumulation and leaching from all pine bark medium. HortScience. 15(6):824-825.

Topp, G.C., J.L. Davis. 1985. Measuremnet of soil water content using time-domain reflectrometry (TDR): a field evaluation. Soil Sci. Soc. Am. J. 49:19-24.

Ton, T., and M. Kopyt. 2003. Phytomonitoring in irrigation scheduling of horticultural crops. Phytech Ltd. Newsletter: Nov.

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

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

Urbano, C.C. 1989. The environmental debate: An industry issue. Amer. Nurseryman. 184(4):69-85.

Valancogne, C., Z. Nasr. 1989. Measuring sap flow in stem of small tress by a heat balanced method. HortScience. 24:383-385.

Wanjura, D.F., D.R. Upchurch, J.R. Mahan. 1995. Control of irrigation scheduling using temperature-time thresholds. Transactions ASAE 38:403-409.

Warren, S. L., and T. E. Bilderback. 2002. Timing of low pressure irrigation affects plant growth and water utilization efficiency. J. Environ. Hort. 20:184-188.

Warren, S.L., T.E. Bilderback. 2004. Irrigation timing: effect on plant growth, photsynthesis, water-use efficiency and substrate temperature. Acta Hort. 644:29-37.

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

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

White, J. W. and J. W. Mastalerz. 1966. Soil moisture as related to container capacity. Proc. Amer. Soc. Hort. Sci.89:758-765.

Whiteside, R. 1989. El Modeno Gardens: Innovative solutions to California’s irrigation runoff restrictions. Grower Talks. 59(2):28-32.

Yeager, T.H., R.D. Wright .1982. Phspherousrequirements of *Ilex crenata* Thunb. Cv Helleri grown in a pine bark medium. J. Amer. Soc. Hort. Sci. 107: 558-562.

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

Yeager, T., R.D Wright, D. Fare, G. Gilliam, J. Johnson, T. Bilderback, R. Zondag. 1993. Six state survey of container nursery nitrate nitrogen runoff. J. Environ. Hort. 11(4): 206-28.

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

Zahreddine, H.G., D.K. Struve, Talhouk, S.N. 2007. Growth and nutrient partitioning of containerized Cercis siliquastrum L. under two fertilizer regimes. Scientia Horticultrae. 112:80-88.

Zur, B. 1976. The pulse irrigation principle for controlled soil wetting. Soil Sci. 122:282-291.

APPENDIX A

Irrigation Controller Code

```
Dim STimerA As Boolean
Dim STimerB As Boolean
Dim STimerC As Boolean
Dim STimerD As Boolean
Dim DataInputEnabledA As Boolean
Dim DataInputEnabledB As Boolean
Dim DataInputEnabledC As Boolean
Dim DataInputEnabledD As Boolean
Dim DataInputEnabledE As Boolean
Dim DataInputEnabledBA As Boolean
Dim DataInputEnabledBB As Boolean
Dim DataInputEnabledBC As Boolean
Dim DataInputEnabledScheduled As Boolean
Dim DataInputEnabledScheduled2 As Boolean
Dim TimerEnabledA As Boolean
Dim TimerEnabledB As Boolean
Dim TimerEnabledC As Boolean
Dim TimerEnabledD As Boolean
Dim TimerEnabledE As Boolean
Dim TimerEnabledBA As Boolean
Dim TimerEnabledBB As Boolean
Dim TimerEnabledBC As Boolean
Dim TimerEnabledScheduled As Boolean
Dim TimerEnabledScheduled2 As Boolean
Dim RestTimerA As Boolean
Dim RestTimerB As Boolean
Dim RestTimerC As Boolean
Dim RestTimerD As Boolean
Dim RestTimerE As Boolean
Dim RestTimerBA As Boolean
Dim RestTimerBB As Boolean
Dim RestTimerBC As Boolean
Sub Start()
EnableSTimerA
```

```
EnableSTimerB
EnableDataInputScheduled
EnableDataInputScheduled2
End Sub
Sub EnableSTimerA()

STimerA = True

ScaleTimerA

End Sub
Sub EnableSTimerB()

STimerB = True
ScaleTimerB

End Sub
Sub EnableSTimerC()

STimerC = True
ScaleTimerC

End Sub
Sub EnableSTimerD()

STimerD = True
ScaleTimerD

End Sub
Sub EnableDataInputA()

 STimerA = False

'button control to turn system on
DataInputEnabledA = True
GetScaleDataA

End Sub

Sub EnableDataInputB()

STimerB = False

'button control to turn system on
```

```
DataInputEnabledB = True
GetScaleDataB

End Sub

Sub EnableDataInputC()

STimerC = False

'button control to turn system on
DataInputEnabledC = True
GetScaleDataC

End Sub

Sub EnableDataInputD()

STimerD = False

'button control to turn system on
DataInputEnabledD = True
GetScaleDataD

End Sub

Sub EnableDataInputE()

'button control to turn system on
DataInputEnabledE = True
GetScaleDataE

End Sub

Sub EnableDataInputBA()

'button control to turn system on
DataInputEnabledBA = True
GetScaleDataBA

End Sub
Sub EnableDataInputBB()

'button control to turn system on
DataInputEnabledBB = True
```

```
GetScaleDataBB

End Sub
Sub EnableDataInputBC()

'button control to turn system on
DataInputEnabledBC = True
GetScaleDataBC

End Sub
Sub EnableDataInputScheduled()

'button control to turn system on
DataInputEnabledScheduled = True
Scheduled

End Sub
Sub EnableDataInputScheduled2()

'button control to turn system on
DataInputEnabledScheduled2 = True
Scheduled2

End Sub
Sub DisableDataInputA()

'button control to turn system off
DataInputEnabledA = False


End Sub
Sub DisableDataInputB()

'button control to turn system off
DataInputEnabledB = False


End Sub
Sub DisableDataInputC()

'button control to turn system off
DataInputEnabledC = False
```

```
End Sub
Sub DisableDataInputD()

'button control to turn system off
DataInputEnabledD = False


End Sub
Sub DisableDataInputE()

'button control to turn system off
DataInputEnabledE = False


End Sub
Sub DisableDataInputBA()

'button control to turn system off
DataInputEnabledBA = False


End Sub
Sub DisableDataInputBB()

'button control to turn system off
DataInputEnabledBB = False


End Sub
Sub DisableDataInputBC()

'button control to turn system off
DataInputEnabledBC = False


End Sub

Sub ScaleTimerA()


Dim R As Long

If STimerA Then
Application.OnTime Now + TimeValue("00:00:06"), "ScaleTimerA"
```

```
Else
Exit Sub
End If

If Sheets(1).Cells(1794, 3) > 0 Then Application.OnTime Now, "EnableDataInputA"

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 3).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 3).Value = 1

End Sub
Sub ScaleTimerB()


Dim R As Long

If STimerB Then
Application.OnTime Now + TimeValue("00:00:06"), "ScaleTimerB"
Else
Exit Sub
End If

If Sheets(1).Cells(1794, 6) > 0 Then Application.OnTime Now, "EnableDataInputB"

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 6).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 6).Value = 1

End Sub
Sub ScaleTimerC()


Dim R As Long

If STimerC Then
Application.OnTime Now + TimeValue("00:00:02"), "ScaleTimerC"
Else
Exit Sub
End If

If Sheets(1).Cells(1794, 9) > 0 Then Application.OnTime Now, "EnableDataInputC"
```

```
' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 9).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 9).Value = 1

End Sub
Sub ScaleTimerD()


Dim R As Long

If STimerD Then
Application.OnTime Now + TimeValue("00:00:02"), "ScaleTimerD"
Else
Exit Sub
End If

If Sheets(1).Cells(1794, 12) > 0 Then Application.OnTime Now, "EnableDataInputD"

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 12).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 12).Value = 1

End Sub
Sub GetScaleDataA()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledA Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:02"), "GetScaleDataA"
Else
  Exit Sub
End If


If Sheets("Sheet1").Cells(1799, 3) > 0 Then Application.OnTime Now, "Stop_DataA"



Application.DisplayAlerts = False   ' disable DDE error messages
```

```
On Error Resume Next              ' ignore errors
C = DDEInitiate("WinWedge", "COM1") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                    ' close the DDE channel
S = F(1)                        ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 3).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 1).Value = Date
Sheets(1).Cells(R, 2).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 3).Value = S

End Sub
Sub GetScaleDataB()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledB Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:02"), "GetScaleDataB"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1799, 6) > 0 Then Application.OnTime Now, "Stop_DataB"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next              ' ignore errors
C = DDEInitiate("WinWedge", "COM2") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                    ' close the DDE channel
S = F(1)                          ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 6).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
```

```
Sheets(1).Cells(R, 4).Value = Date
Sheets(1).Cells(R, 5).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 6).Value = S

End Sub
Sub GetScaleDataC()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledC Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:02"), "GetScaleDataC"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1799, 9) > 0 Then Application.OnTime Now, "Stop_DataC"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM3") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 9).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 7).Value = Date
Sheets(1).Cells(R, 8).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 9).Value = S

End Sub
Sub GetScaleDataD()

Dim C As Long
Dim F As Variant
```

```
Dim S As String
Dim R As Long

If DataInputEnabledD Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:02"), "GetScaleDataD"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1799, 12) > 0 Then Application.OnTime Now, "Stop_DataD"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM4") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 12).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 10).Value = Date
Sheets(1).Cells(R, 11).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 12).Value = S

End Sub
Sub GetScaleDataE()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledE Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "GetScaleDataE"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1800, 15) > 0 Then Application.OnTime Now, "Stop_DataE"
```

```
Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM6") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 15).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 13).Value = Date
Sheets(1).Cells(R, 14).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 15).Value = S

End Sub
Sub GetScaleDataBA()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledBA Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "GetScaleDataBA"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1800, 18) > 0 Then Application.OnTime Now, "Stop_DataBA"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM10") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string
```

```
' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 18).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 16).Value = Date
Sheets(1).Cells(R, 17).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 18).Value = S

End Sub
Sub GetScaleDataBB()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledBB Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:02"), "GetScaleDataBB"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1800, 21) > 0 Then Application.OnTime Now, "Stop_DataBB"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM4") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 21).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 19).Value = Date
Sheets(1).Cells(R, 20).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 21).Value = S

End Sub
```

```
Sub GetScaleDataBC()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

If DataInputEnabledBC Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "GetScaleDataBC"
Else
  Exit Sub
End If

If Sheets("Sheet1").Cells(1800, 24) > 0 Then Application.OnTime Now, "Stop_DataBC"



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM12") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(1).Cells(1800, 24).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(1).Cells(R, 22).Value = Date
Sheets(1).Cells(R, 23).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(1).Cells(R, 24).Value = S

End Sub
Sub Stop_DataA()

'turn system off and make calculation
DataInputEnabledA = False

'make calculation
Application.OnTime Now, "Get_DataA"

End Sub
Sub Stop_DataB()
```

```
'turn system off and make calculation
DataInputEnabledB = False

'make calculation
Application.OnTime Now, "Get_DataB"

End Sub
Sub Stop_DataC()

'turn system off and make calculation
DataInputEnabledC = False

'make calculation
Application.OnTime Now, "Get_DataC"

End Sub
Sub Stop_DataD()

'turn system off and make calculation
DataInputEnabledD = False

'make calculation
Application.OnTime Now, "Get_DataD"

End Sub
Sub Stop_DataE()

'turn system off and make calculation
DataInputEnabledE = False

'make calculation
Application.OnTime Now, "Get_DataE"

End Sub
Sub Stop_DataBA()

'turn system off and make calculation
DataInputEnabledBA = False

'make calculation
Application.OnTime Now, "Get_DataBA"

End Sub
```

```
Sub Stop_DataBB()

'turn system off and make calculation
DataInputEnabledBB = False

'make calculation
Application.OnTime Now, "Get_DataBB"

End Sub
Sub Stop_DataBC()

'turn system off and make calculation
DataInputEnabledBC = False

'make calculation
Application.OnTime Now, "Get_DataBC"

End Sub
Sub Get_DataA()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = Sheets(1).Cells(1802, 3) - Sheets(1).Cells(1801, 3)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 3).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 1).Value = Date
Sheets(2).Cells(R, 2).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 3).Value = Sheets(1).Cells(1801, 3)



If T > 0.05 Then Application.OnTime Now, "Valve_OnA"

If T < 0.05 Then Application.OnTime Now, "Start_RestA"

If T = 0.05 Then Application.OnTime Now, "Start_RestA"
```

```
End Sub
Sub Get_DataB()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = Sheets(1).Cells(1802, 6) - Sheets(1).Cells(1801, 6)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 7).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 5).Value = Date
Sheets(2).Cells(R, 6).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 7).Value = Sheets(1).Cells(1801, 6)



If T > 0.05 Then Application.OnTime Now, "Valve_OnB"

If T < 0.05 Then Application.OnTime Now, "Start_RestB"

If T = 0.05 Then Application.OnTime Now, "Start_RestB"

End Sub
Sub Get_DataC()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = Sheets(1).Cells(1802, 9) - Sheets(1).Cells(1801, 9)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 11).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 9).Value = Date
Sheets(2).Cells(R, 10).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
```

```
Sheets(2).Cells(R, 11).Value = Sheets(1).Cells(1801, 9)


If T > 0.05 Then Application.OnTime Now, "Start_RestC"

If T < 0.05 Then Application.OnTime Now, "Start_RestC"

If T = 0.05 Then Application.OnTime Now, "Start_RestC"

End Sub
Sub Get_DataD()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = Sheets(1).Cells(1802, 12) - Sheets(1).Cells(1801, 12)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 15).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 13).Value = Date
Sheets(2).Cells(R, 14).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 15).Value = Sheets(1).Cells(1801, 12)


If T > 0.05 Then Application.OnTime Now, "Start_RestD"

If T < 0.05 Then Application.OnTime Now, "Start_RestD"

If T = 0.05 Then Application.OnTime Now, "Start_RestD"

End Sub
Sub Get_DataE()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long
```

```
T = 54 - Sheets(1).Cells(1801, 15)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 19).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 17).Value = Date
Sheets(2).Cells(R, 18).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 19).Value = Sheets(1).Cells(1801, 15)

' find the first empty cell at the bottom of the column 3 of sheet(1)
R1 = Sheets(2).Cells(65000, 20).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R1, 20).Value = T

If T > 0.02 Then Application.OnTime Now, "Valve_OnE"

If T < 0.02 Then Application.OnTime Now, "Start_RestE"

If T = 0.02 Then Application.OnTime Now, "Start_RestE"

End Sub
Sub Get_DataBA()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = 35 - Sheets(1).Cells(1801, 18)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 23).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 21).Value = Date
Sheets(2).Cells(R, 22).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 23).Value = Sheets(1).Cells(1801, 18)

' find the first empty cell at the bottom of the column 3 of sheet(1)
R1 = Sheets(2).Cells(65000, 24).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
```

```
Sheets(2).Cells(R1, 24).Value = T

If T > 0.02 Then Application.OnTime Now, "Valve_OnBA"

If T < 0.02 Then Application.OnTime Now, "Start_RestBA"

If T = 0.02 Then Application.OnTime Now, "Start_RestBA"

End Sub
Sub Get_DataBB()

Dim S As String
Dim R As Long
Dim T As String
Dim R1 As Long
Dim R2 As Long

T = 53 - Sheets(1).Cells(1801, 21)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 27).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 25).Value = Date
Sheets(2).Cells(R, 26).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 27).Value = Sheets(1).Cells(1801, 21)

' find the first empty cell at the bottom of the column 3 of sheet(1)
R1 = Sheets(2).Cells(65000, 28).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R1, 28).Value = T

If T > 0.02 Then Application.OnTime Now, "Start_RestBB"

If T < 0.02 Then Application.OnTime Now, "Start_RestBB"

If T = 0.02 Then Application.OnTime Now, "Start_RestBB"

End Sub
Sub Get_DataBC()

Dim S As String
Dim R As Long
Dim T As String
```

```
Dim R1 As Long
Dim R2 As Long

T = 61 - Sheets(1).Cells(1801, 24)

' find the first empty cell at the bottom of the column 3 of sheet(2)
R = Sheets(2).Cells(65000, 31).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 29).Value = Date
Sheets(2).Cells(R, 30).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(2)
Sheets(2).Cells(R, 31).Value = Sheets(1).Cells(1801, 24)

' find the first empty cell at the bottom of the column 3 of sheet(1)
R1 = Sheets(2).Cells(65000, 32).End(xlUp).Row + 1
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R1, 32).Value = T

If T > 0.02 Then Application.OnTime Now, "Start_RestBC"

If T < 0.02 Then Application.OnTime Now, "Start_RestBC"

If T = 0.02 Then Application.OnTime Now, "Start_RestBC"

End Sub
Sub Valve_OnA()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACA',13,10)]"
DDETerminate Chan

TimerEnabledA = True

Application.OnTime Now, " EnableTimerA"

End Sub
Sub Valve_OnB()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACB',13,10)]"
DDETerminate Chan

TimerEnabledB = True
```

```
Application.OnTime Now, " EnableTimerB"

End Sub
Sub Valve_OnC()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACC',13,10)]"
DDETerminate Chan

TimerEnabledC = True

Application.OnTime Now, " EnableTimerC"

End Sub
Sub Valve_OnD()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACE',13,10)]"
DDETerminate Chan

TimerEnabledD = True

Application.OnTime Now, " EnableTimerD"

End Sub
Sub Valve_OnE()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACE',13,10)]"
DDETerminate Chan

TimerEnabledE = True

Application.OnTime Now, " EnableTimerE"

End Sub
Sub Valve_OnBA()

Chan = DDEInitiate("WINWEDGE", "COM13")
DDEExecute Chan, "[SENDOUT('BCE',13,10)]"
DDETerminate Chan

TimerEnabledBA = True
```

```
Application.OnTime Now, " EnableTimerBA"

End Sub
Sub EnableTimerA()

TimerEnabledA = True

Application.OnTime Now, "TimerA"

End Sub
Sub EnableTimerB()

TimerEnabledB = True

Application.OnTime Now, "TimerB"

End Sub
Sub EnableTimerC()

TimerEnabledC = True

Application.OnTime Now, "TimerC"

End Sub
Sub EnableTimerD()

TimerEnabledD = True

Application.OnTime Now, "TimerD"

End Sub
Sub EnableTimerE()

TimerEnabledE = True

Application.OnTime Now, "TimerE"

End Sub
Sub EnableTimerBA()

TimerEnabledBA = True

Application.OnTime Now, "TimerBA"
```

```
End Sub
Sub TimerA()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledA Then Application.OnTime Now + TimeValue("00:00:01"), "TimerA"
If TimerEnabledA Then S = Sheets(1).Cells(1801, 3)

T = (Sheets(1).Cells(1802, 3) - S) * 60
R = T

R = Sheets(3).Cells(65000, 1).End(xlUp).Row + 1
Sheets(3).Cells(R, 1).Value = T

If Sheets(3).Cells(T, 1) > 0 Then Application.OnTime Now, "Valve_OffA"


End Sub


Sub TimerB()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledB Then Application.OnTime Now + TimeValue("00:00:01"), "TimerB"
If TimerEnabledB Then S = Sheets(1).Cells(1801, 6)

T = (Sheets(1).Cells(1802, 6) - S) * 60 + 1
R = T

R = Sheets(3).Cells(65000, 3).End(xlUp).Row + 1
Sheets(3).Cells(R, 3).Value = T

If Sheets(3).Cells(T, 3) > 0 Then Application.OnTime Now, "Valve_OffB"


End Sub
Sub TimerC()

Dim T As Integer
```

```
Dim R As Long
Dim S As Single

If TimerEnabledC Then Application.OnTime Now + TimeValue("00:00:01"), "TimerC"
If TimerEnabledC Then S = Sheets(1).Cells(1801, 9)

T = (Sheets(1).Cells(1802, 9) - S) * 60 + 1
R = T

R = Sheets(3).Cells(65000, 5).End(xlUp).Row + 1
Sheets(3).Cells(R, 5).Value = T

If Sheets(3).Cells(T, 5) > 0 Then Application.OnTime Now, "Valve_OffC"


End Sub
Sub TimerD()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledD Then Application.OnTime Now + TimeValue("00:00:01"), "TimerD"
If TimerEnabledD Then S = Sheets(1).Cells(1801, 12)

T = (Sheets(1).Cells(1802, 12) - S) * 60 + 1
R = T

R = Sheets(3).Cells(65000, 7).End(xlUp).Row + 1
Sheets(3).Cells(R, 7).Value = T

If Sheets(3).Cells(T, 7) > 0 Then Application.OnTime Now, "Valve_OffD"


End Sub
Sub TimerE()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledE Then Application.OnTime Now + TimeValue("00:00:01"), "TimerE"
If TimerEnabledE Then S = Sheets(1).Cells(1801, 15)
```

```
T = (36 - S) * 60 + 1
R = T

R = Sheets(3).Cells(65000, 9).End(xlUp).Row + 1
Sheets(3).Cells(R, 9).Value = T

If Sheets(3).Cells(T, 9) > 0 Then Application.OnTime Now, "Valve_OffE"


End Sub
Sub TimerBA()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledBA Then Application.OnTime Now + TimeValue("00:00:01"),
"TimerBA"
If TimerEnabledBA Then S = Sheets(1).Cells(1801, 18)

T = (35 - S) * 60 + 1
R = T

R = Sheets(3).Cells(65000, 11).End(xlUp).Row + 1
Sheets(3).Cells(R, 11).Value = T

If Sheets(3).Cells(T, 11) > 0 Then Application.OnTime Now, "Valve_OffBA"


End Sub
Sub Valve_OffA()

TimerEnabledA = False

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOA',13,10)]"
DDETerminate Chan

Sheets("Sheet3").Select
Range("A1:A6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestA"
```

```
End Sub
Sub Valve_OffB()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOB',13,10)]"
DDETerminate Chan

TimerEnabledB = False
Sheets("Sheet3").Select
Range("C1:C6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestB"

End Sub
Sub Valve_OffC()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOC',13,10)]"
DDETerminate Chan

TimerEnabledC = False
Sheets("Sheet3").Select
Range("E1:E6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestC"

End Sub
Sub Valve_OffD()

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOE',13,10)]"
DDETerminate Chan

TimerEnabledD = False
Sheets("Sheet3").Select
Range("G1:G6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestD"

End Sub
Sub Valve_OffE()
```

```
Chan = DDEInitiate("WINWEDGE", "COM9")
DDEExecute Chan, "[SENDOUT('AOE',13,10)]"
DDETerminate Chan

TimerEnabledE = False
Sheets("Sheet3").Select
Range("I1:I6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestE"

End Sub
Sub Valve_OffBA()

Chan = DDEInitiate("WINWEDGE", "COM9")
DDEExecute Chan, "[SENDOUT('BOE',13,10)]"
DDETerminate Chan

TimerEnabledBA = False
Sheets("Sheet3").Select
Range("K1:K6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestBA"

End Sub
Sub Start_RestA()
RestTimerA = True
Application.OnTime Now, "RestA"
End Sub
Sub Start_RestB()
RestTimerB = True
Application.OnTime Now, "RestB"
End Sub
Sub Start_RestC()
RestTimerC = True
Application.OnTime Now, "RestC"
End Sub
Sub Start_RestD()
RestTimerD = True
Application.OnTime Now, "RestD"
End Sub
Sub Start_RestE()
```

```
RestTimerE = True
Application.OnTime Now, "RestE"
End Sub
Sub Start_RestBA()
RestTimerBA = True
Application.OnTime Now, "RestBA"
End Sub
Sub Start_RestBB()
RestTimerBB = True
Application.OnTime Now, "RestBB"
End Sub
Sub Start_RestBC()
RestTimerBC = True
Application.OnTime Now, "RestBC"
End Sub
Sub RestA()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerA Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:12"), "RestA"
Else
  Exit Sub
End If

If Sheets("Sheet3").Cells(25, 2) > 0 Then RestTimerA = False

If Sheets("Sheet3").Cells(25, 2) > 0 Then Application.OnTime Now, "Stop_RestA"


R = Sheets(3).Cells(25, 2).End(xlUp).Row + 1
Sheets(3).Cells(R, 2).Value = 1




End Sub
Sub RestB()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerB Then    ' run again in 5 seconds
```

```
  Application.OnTime Now + TimeValue("00:00:12"), "RestB"
Else
  Exit Sub
End If
If Sheets("Sheet3").Cells(25, 4) > 0 Then RestTimerB = False
If Sheets("Sheet3").Cells(25, 4) > 0 Then Application.OnTime Now, "Stop_RestB"


R = Sheets(3).Cells(25, 4).End(xlUp).Row + 1
Sheets(3).Cells(R, 4).Value = 1




End Sub
Sub RestC()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerC Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:012"), "RestC"
Else
  Exit Sub
End If
If Sheets("Sheet3").Cells(25, 6) > 0 Then RestTimerC = False
If Sheets("Sheet3").Cells(25, 6) > 0 Then Application.OnTime Now, "Stop_RestC"


R = Sheets(3).Cells(25, 6).End(xlUp).Row + 1
Sheets(3).Cells(R, 6).Value = 1




End Sub
Sub RestD()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerD Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:012"), "RestD"
Else
```

```
  Exit Sub
End If
If Sheets("Sheet3").Cells(25, 8) > 0 Then RestTimerD = False
If Sheets("Sheet3").Cells(25, 8) > 0 Then Application.OnTime Now, "Stop_RestD"


R = Sheets(3).Cells(25, 8).End(xlUp).Row + 1
Sheets(3).Cells(R, 8).Value = 1




End Sub
Sub RestE()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerE Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "RestE"
Else
  Exit Sub
End If
If Sheets("Sheet3").Cells(5, 10) > 0 Then RestTimerE = False
If Sheets("Sheet3").Cells(5, 10) > 0 Then Application.OnTime Now, "Stop_RestE"


R = Sheets(3).Cells(5, 10).End(xlUp).Row + 1
Sheets(3).Cells(R, 10).Value = 1




End Sub
Sub RestBA()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerBA Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "RestBA"
Else
  Exit Sub
End If
```

```
If Sheets("Sheet3").Cells(5, 12) > 0 Then RestTimerBA = False
If Sheets("Sheet3").Cells(5, 12) > 0 Then Application.OnTime Now, "Stop_RestBA"


R = Sheets(3).Cells(5, 12).End(xlUp).Row + 1
Sheets(3).Cells(R, 12).Value = 1




End Sub
Sub RestBB()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerBB Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "RestBB"
Else
  Exit Sub
End If
If Sheets("Sheet3").Cells(5, 14) > 0 Then RestTimerBB = False
If Sheets("Sheet3").Cells(5, 14) > 0 Then Application.OnTime Now, "Stop_RestBB"


R = Sheets(3).Cells(5, 14).End(xlUp).Row + 1
Sheets(3).Cells(R, 14).Value = 1




End Sub
Sub RestBC()
Dim T As Integer
Dim R As Long
Dim S As Integer

If RestTimerBC Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "RestBC"
Else
  Exit Sub
End If
If Sheets("Sheet3").Cells(5, 16) > 0 Then RestTimerBC = False
If Sheets("Sheet3").Cells(5, 16) > 0 Then Application.OnTime Now, "Stop_RestBC"
```

```
R = Sheets(3).Cells(5, 16).End(xlUp).Row + 1
Sheets(3).Cells(R, 16).Value = 1




End Sub
Sub Stop_RestA()

RestTimerA = False
Sheets("Sheet3").Select
Range("B1:B25").Select
Selection.ClearContents

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOA',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsA"

End Sub

Sub Stop_RestB()

RestTimerB = False
Sheets("Sheet3").Select
Range("D1:D25").Select
Selection.ClearContents

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOB',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsB"

End Sub
Sub Stop_RestC()

RestTimerC = False
Sheets("Sheet3").Select
Range("F1:F25").Select
Selection.ClearContents
```

```
Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOC',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsC"

End Sub
Sub Stop_RestD()

RestTimerD = False
Sheets("Sheet3").Select
Range("H1:H25").Select
Selection.ClearContents

Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOD',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsD"

End Sub
Sub Stop_RestE()

RestTimerE = False
Sheets("Sheet3").Select
Range("J1:J10").Select
Selection.ClearContents

Chan = DDEInitiate("WINWEDGE", "COM9")
DDEExecute Chan, "[SENDOUT('AOE',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsE"

End Sub
Sub Stop_RestBA()

RestTimerBA = False
Sheets("Sheet3").Select
Range("L1:L10").Select
Selection.ClearContents

Chan = DDEInitiate("WINWEDGE", "COM9")
```

```
DDEExecute Chan, "[SENDOUT('BOE',13,10)]"
DDETerminate Chan

Application.OnTime Now, "Clear_ContentsBA"

End Sub
Sub Stop_RestBB()

RestTimerBB = False
Sheets("Sheet3").Select
Range("N1:N10").Select
Selection.ClearContents



Application.OnTime Now, "Clear_ContentsBB"

End Sub
Sub Stop_RestBC()

RestTimerBC = False
Sheets("Sheet3").Select
Range("P1:P10").Select
Selection.ClearContents



Application.OnTime Now, "Clear_ContentsBC"

End Sub
Sub Clear_ContentsA()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("A2:C1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "GetWetWeightA"

End Sub
Sub Clear_ContentsB()

'delete all samples weights over the past interval (?min)
```

```
Sheets("Sheet1").Select
Range("D2:F1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "GetWetWeightB"

End Sub
Sub Clear_ContentsC()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("G2:I1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "GetWetWeightC"

End Sub
Sub Clear_ContentsD()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("J2:L1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "GetWetWeightD"

End Sub
Sub Clear_ContentsE()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("M2:O1800").Select
Selection.ClearContents

'move to next sub routine (Break)
DataInputEnabledA = True
Application.OnTime Now, "BreakE"

End Sub
Sub Clear_ContentsBA()
```

```
'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("P2:R1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "BreakBA"

End Sub
Sub Clear_ContentsBB()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("S2:U1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "BreakBB"

End Sub
Sub Clear_ContentsBC()

'delete all samples weights over the past interval (?min)
Sheets("Sheet1").Select
Range("V2:X1800").Select
Selection.ClearContents

'move to next sub routine (Break)
Application.OnTime Now, "BreakBC"

End Sub

Sub GetWetWeightA()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
```

```
C = DDEInitiate("WinWedge", "COM1") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 3).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 1).Value = Date
Sheets(2).Cells(R, 2).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 3).Value = S

Application.OnTime Now, "BreakA"

End Sub
Sub GetWetWeightB()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM2") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 7).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 5).Value = Date
Sheets(2).Cells(R, 6).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 7).Value = S

Application.OnTime Now, "BreakB"
```

```
End Sub
Sub GetWetWeightC()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM3") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 11).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 9).Value = Date
Sheets(2).Cells(R, 10).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 11).Value = S

Application.OnTime Now, "BreakC"

End Sub
Sub GetWetWeightD()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM4") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
```

```
S = F(1)                        ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 15).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 13).Value = Date
Sheets(2).Cells(R, 14).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 15).Value = S

Application.OnTime Now, "BreakD"

End Sub
Sub BreakA()

'resume loop at get scale data
DataInputEnabledA = False
Application.OnTime Now, "EnableSTimerA"

End Sub

Sub BreakB()

'resume loop at get scale data
DataInputEnabledB = False
Application.OnTime Now, "EnableSTimerB"

End Sub
Sub BreakC()

'resume loop at get scale data
DataInputEnabledC = False
Application.OnTime Now, "EnableDataInputScheduled"

End Sub

Sub BreakD()

'resume loop at get scale data
DataInputEnabledD = False
Application.OnTime Now, "EnableDataInputScheduled2"

End Sub
Sub BreakE()
```

```
'resume loop at get scale data
DataInputEnabledE = False
Application.OnTime Now, "EnableDataInputE"

End Sub
Sub BreakBA()

'resume loop at get scale data
DataInputEnabledBA = False
Application.OnTime Now, "EnableDataInputBA"

End Sub
Sub BreakBB()

'resume loop at get scale data
DataInputEnabledBB = False
Application.OnTime Now, "EnableDataInputBB"

End Sub
Sub BreakBC()

'resume loop at get scale data
DataInputEnabledBC = False
Application.OnTime Now, "EnableDataInputBC"

End Sub

Sub Scheduled()



If DataInputEnabledScheduled Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "Scheduled"
Else
  Exit Sub
End If

' date and time stamp the data in columns A and B
Sheets(4).Cells(1, 1).Value = Date
Sheets(4).Cells(1, 2).Value = Time
```

```
If Sheets(4).Cells(1, 2) = Sheets(4).Cells(2, 2) Then Application.OnTime Now,
"Valve_OnScheduledtop"
If Sheets(4).Cells(1, 2) = Sheets(4).Cells(3, 2) Then Application.OnTime Now,
"Valve_OnScheduledbottom"


End Sub
Sub Valve_OnScheduledtop()


Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

DataInputEnabledScheduled = False



Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next               ' ignore errors
C = DDEInitiate("WinWedge", "COM3") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")      ' get the data from Field(1) in WinWedge
DDETerminate C                     ' close the DDE channel
S = F(1)                           ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 11).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 9).Value = Date
Sheets(2).Cells(R, 10).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 11).Value = S



Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACC',13,10)]"
DDETerminate Chan
```

```
Application.OnTime Now, " EnableTimerScheduled"

End Sub
Sub Valve_OnScheduledbottom()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

DataInputEnabledScheduled = False


Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next               ' ignore errors
C = DDEInitiate("WinWedge", "COM3") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                     ' close the DDE channel
S = F(1)                           ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 11).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 9).Value = Date
Sheets(2).Cells(R, 10).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 11).Value = S


Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACC',13,10)]"
DDETerminate Chan



Application.OnTime Now, "EnableTimerScheduled"

End Sub
Sub EnableTimerScheduled()

TimerEnabledScheduled = True

Application.OnTime Now, "TimerScheduled"
```

```
End Sub
Sub TimerScheduled()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledScheduled Then Application.OnTime Now + TimeValue("00:00:15"),
"TimerScheduled"


T = Sheets(4).Cells(2, 1)
R = T

R = Sheets(4).Cells(65000, 5).End(xlUp).Row + 1
Sheets(4).Cells(R, 5).Value = T

If Sheets(4).Cells(T, 5) > 0 Then Application.OnTime Now, "Valve_OffScheduled"


End Sub
Sub Valve_OffScheduled()


Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOC',13,10)]"
DDETerminate Chan

TimerEnabledScheduled = False

Sheets("Sheet4").Select
Range("E1:E6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestC"

End Sub
Sub Scheduled2()



If DataInputEnabledScheduled2 Then    ' run again in 5 seconds
  Application.OnTime Now + TimeValue("00:00:01"), "Scheduled2"
```

```
Else
  Exit Sub
End If

' date and time stamp the data in columns A and B
Sheets(4).Cells(1, 6).Value = Date
Sheets(4).Cells(1, 7).Value = Time




If Sheets(4).Cells(1, 7) = Sheets(4).Cells(2, 7) Then Application.OnTime Now,
"Valve_OnScheduled2top"
If Sheets(4).Cells(1, 7) = Sheets(4).Cells(3, 7) Then Application.OnTime Now,
"Valve_OnScheduled2bottom"

End Sub
Sub Valve_OnScheduled2top()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

DataInputEnabledScheduled2 = False


Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM4") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 15).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 13).Value = Date
Sheets(2).Cells(R, 14).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 15).Value = S
```

```
Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACD',13,10)]"
DDETerminate Chan



Application.OnTime Now, " EnableTimerScheduled2"

End Sub
Sub Valve_OnScheduled2bottom()

Dim C As Long
Dim F As Variant
Dim S As String
Dim R As Long

DataInputEnabledScheduled2 = False

Application.DisplayAlerts = False   ' disable DDE error messages
On Error Resume Next                ' ignore errors
C = DDEInitiate("WinWedge", "COM4") ' open a connection to WinWedge on the
specified port
F = DDERequest(C, "Field(1)")       ' get the data from Field(1) in WinWedge
DDETerminate C                      ' close the DDE channel
S = F(1)                            ' convert the variant array data to a string

' find the first empty cell at the bottom of the column 3 of sheet(1)
R = Sheets(2).Cells(1800, 15).End(xlUp).Row + 1
' date and time stamp the data in columns A and B
Sheets(2).Cells(R, 13).Value = Date
Sheets(2).Cells(R, 14).Value = Time
' write the data to the bottom row of column C Cells(R, 3) in sheet(1)
Sheets(2).Cells(R, 15).Value = S



Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('ACD',13,10)]"
DDETerminate Chan
```

```
Application.OnTime Now, " EnableTimerScheduled2"

End Sub
Sub EnableTimerScheduled2()

TimerEnabledScheduled2 = True

Application.OnTime Now, "TimerScheduled2"

End Sub
Sub TimerScheduled2()

Dim T As Integer
Dim R As Long
Dim S As Single

If TimerEnabledScheduled2 Then Application.OnTime Now + TimeValue("00:00:15"),
"TimerScheduled2"


T = Sheets(4).Cells(2, 6)
R = T

R = Sheets(4).Cells(65000, 8).End(xlUp).Row + 1
Sheets(4).Cells(R, 8).Value = T

If Sheets(4).Cells(T, 8) > 0 Then Application.OnTime Now, "Valve_OffScheduled2"


End Sub
Sub Valve_OffScheduled2()


Chan = DDEInitiate("WINWEDGE", "COM5")
DDEExecute Chan, "[SENDOUT('AOD',13,10)]"
DDETerminate Chan

TimerEnabledScheduled2 = False
Sheets("Sheet4").Select
Range("H1:H6500").Select
Selection.ClearContents

Application.OnTime Now, "Start_RestD"
```

```
End Sub
```