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Use of Effluent Volumes to Control Leaching in Nursery Container Crops With Tipping Bucket Sensors

Maureen Thiessen
Louisiana State University and Agricultural and Mechanical College

USE OF EFFLUENT VOLUMES TO CONTROL LEACHING IN NURSERY CONTAINER CROPS WITH TIPPING BUCKET SENSORS

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Maureen Thiessen
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To

Endurance.

To everyone who thinks they want to give up—keep pushing and you will truly see what you can handle, and what you would have missed had you stopped short of your goal.

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ABSTRACT

Overirrigating container crops can lead to increased nutrient leaching and negatively impact water quality. Leaching is implemented to reduce substrate salinity. "Leaching fraction" (effluent volume/irrigation volume) has been described by best management practices to monitor irrigation efficiency. Recommendations and methods for controlling leaching fraction can greatly vary. Therefore, two studies were conducted to test the accuracy of attaining targeted leaching fractions compared to the accuracy of leaching targeted percentages of container capacity. In the first study, the effects of container size and substrate moisture content were tested on each method. Three container sizes of pine bark substrate at three moisture deficits were irrigated to achieve targeted leaching fractions of 0%, 20%, 40%, and 60% of applied irrigation. After leaching, effluent was collected and actual leaching fractions were calculated. Actual leaching fractions were higher than treatment targets, and varied according to substrate moisture content. When irrigation and effluent volumes were compared to container capacity, a linear relationship (R^2>92%) was found between percent container capacity leached at irrigation termination and actual percent of container capacity leached, regardless of substrate moisture and container size. Salt concentrations were measured on effluent samples collected from volumetric intervals during leaching, and were higher in initial samples. In the second study, effects of rooting and time on container capacity, particle size distribution, and the accuracy of leaching based on container capacity were investigated. *Taxodium distichum* liners planted into 10.4L containers were sampled at three time intervals during growth for container capacity, and were irrigated until a proportion of container capacity (0%, 10%, 30%, or 50%) had leached. After leaching, effluent was collected and actual percentage of container capacity leached was calculated. Significant changes were seen in container capacity and rooting by the end of the growth period; however, leaching based upon container capacity retained high accuracy. Controlling container

effluent as a percent of container capacity is accurate despite changes in container size, moisture deficit, container capacity, and rooting, and not only provides a more streamlined approach for container salt removal, but also a method to account for irrigation volumes that could improve irrigation efficiency during container production.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Introduction

Improving irrigation efficiency has been of particular interest to nurserymen within the past two decades. Irrigation practices for the container industry traditionally lack precision and efficiency due to the lack of inexpensive instrumentation and simple protocols that do not sacrifice plant quality. To provide adequate moisture and control substrate salinity, growers have typically applied copious amounts of water and fertilizers, thus increasing the potential for runoff and evaporation. Simple, accurate, and inexpensive methods for improving irrigation and leaching efficiency have been slow to enter the ornamental industry. In anticipation of a tighter economy and increased environmental regulation, growers cannot afford unnecessary cultural practices or high violation fines. Nor can they afford to lose sales as a result of reduced plant quality. Therefore, continued research is needed to provide more efficient methods of increasing nursery production efficiency.

Practices such as microirrigation, combined with cyclic application, have already been shown to increase water application efficiency. Other methods used to determine the volume and frequency of irrigation include evapotranspiration modeling, monitoring container capacity, and monitoring substrate moisture. However, lack of reliable models and high costs make these methods impractical for commercial application. Managing and monitoring container effluent using tipping bucket sensors can reduce irrigation and runoff, as well as ensure toxic salt concentrations are leached. Fertilizers accumulate in the container profile when controlled-release fertilizers break down faster than plant uptake, and irrigation is reduced so they cannot be flushed out as easily. Thus, it is recommended that growers leach a certain fraction of applied irrigation, known as leaching fraction. Reduction of leaching fraction has been shown to increase

efficiency as well as reduce polluted runoff, but has only been managed efficiently using complicated gravimetric systems. Leaching a certain fraction of container capacity may be easier than leaching a certain fraction of applied irrigation, as well as more accurate, and can be done using the same tools.

Literature Review

Water Resources and Environmental Concern

Freshwater is one of the planet's most important resources, but makes up only 4% of the total water supply on earth. Of that, only one-fourth is in a form suitable for human and industry consumption (Press, Siever, Grotzinger, and Jordan, 2004). This poses a challenge to industries, such as agriculture, that consume large quantities of water. Increasing population, suburban sprawl into agricultural production areas, and more sensitive technology have raised environmental awareness among the general public (Bolusky and Regelbrugge, 1992). This has resulted in legislation regulating consumption and surface runoff quality of watersheds. In 1972, the federal government enacted the Federal Clean Water Act that set limits, or total maximum daily loads (TMDLs), for contaminants in all watersheds. The act regulated point-source pollution, while allowing state governments to regulate non-point source pollution, such as runoff. For example, in California, where agriculture accounts for 85% of the state's water consumption, groundwater contamination with nitrates and pesticides have contributed to the passing of the California Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65), and the Ground Water Protection Program (Kabashima, 1993). In addition, a rapidly growing population and recurrent periods of drought have limited the state's water supply and raised cost.

Although the container nursery industry is not responsible for the majority of this usage and runoff, the intensive nature of container plant production has caught the attentions of state

legislatures. Limits on water usage currently exist in California, Florida, North Carolina, Texas, Oregon, and other states (Beeson, Arnold, Bilderback, Bolusky, Chandler, Gramling, Lea-Cox, Harris, Klinger, Mathers, Ruter, and Yeager, 2004). In order to attain quality saleable plants, nurseries also must apply large amounts of fertilizers (often injected through irrigation systems) and pesticides. These substances can run off of nursery property and into lakes, streams, ponds, and groundwater, making nurseries a potential environmental threat (Colangelo & Brand, 2001; Mangiafico, Newman, Merhaut, Gan, Faber, and Wu, 2008). There are also laws regulating contaminant concentrations in nursery runoff in at least Maryland, Delaware, and California (Beeson et al., 2004). For example, in 1998, Maryland required its growers to draft nitrogen and phosphorus management plans through its Water Quality Improvement Act (Lea-Cox & Ross, 2001). Similar requirements were implemented in California by its Regional Water Quality Control Board (Kabashima, 1993). Such legislation is expected to increase. The United States Environmental Protection Agency (USEPA), as well as state governments, are currently working to set watershed TDMLs specifically for NO_3-N and other plant-essential nutrients (Taylor, White, Handler, Klaine, and Whitwell, 2006; Wilson, Albano, Mozdzen, and Riiska, 2010). Nursery growers are aware of these issues and are generally concerned with rising attention to contaminated runoff (J. Trimmer, personal communication, September 6, 2011; Urbano, 1989).

Nature of Container Plant Production

Growing substrate characteristics and container dimensions make nursery crop production very intensive. A plant must absorb all needed water and nutrients through a root system and substrate volume that are unnaturally restricted to the size of its container (Bunt, 1988; Gilman and Beeson, 1996). This has several implications. The growing substrate must be able to provide adequate water, nutrients, and oxygen to the root system. Ideally it would have a high water-holding capacity, suitable cation-exchange capacity, and high air-filled porosity

(Lieth, 1996). However, a growth substrate must also have good drainage because the relative shallowness of containers compared to field conditions can cause perched water tables and anoxic conditions in the lower half of the container. As a result, only a small volume of water is available to the plant, which can be quickly depleted. This necessitates frequent irrigation (Bunt, 1988). Additionally, in comparison with mineral soils, growth substrates generally have very low cation-exchange capacities. The principle components of substrate used in the southeastern U.S. are generally pine bark, sand, and sphagnum peat (Yeager, Gilliam, Bilderback, Fare, Niemiera, and Tilt, 1997). While peat has a high cation-exchange capacity, most mixes for larger containers consist mostly of pine bark. Pine bark is added to increase aeration and drainage, but its low surface area gives it a low ion-exchange capacity. Consequently, nitrogen and mineral nutrients are easily leached when container plants are overwatered (Bunt, 1988; Wilson et al. 2010).

In the USEPA Gold Book (1986), a nitrate concentration of 10mg/L was set as a limit for domestic (potable) water supply (USEPA, 1986). However, growing concerns of accelerated eutrophication and algal blooms in surface waters are leading to the development of numeric nutrient criteria to help manage nitrogen and phosphorus pollution (USEPA, 2011c). The EPA has published ecoregion-specific reference conditions for nitrogen and phosphorus believed to reflect minimal impact by human waste. These concentrations generally fall between 5 and 50 μg/L for phosphorus and 0.1 and 1 mg/L for nitrogen (USEPA, 2011). In 1993, a survey was conducted on six Eastern-U.S. nurseries to determine NO_3-N levels in bed and site runoff (Yeager, Wright, Fare, Gilliam, Johnson, Bilderback, and Zondag, 1993). When using controlled-release fertilizers, runoff concentrations ranged from 0.5 to 33mg/L, with averages under the 10mg/L EPA limit. When fertigation was used in addition to CRF, however, concentrations ranged from 0.1 to 135mg/L, with an average of 20mg/L leaving production beds (Yeager et al., 1993). More recently, a nursery runoff study conducted on primarily 50-L

containers was performed to evaluate a wetland nutrient removal system. Samples of untreated runoff leaving the production area contained between 11.1 and 29.9mg/L oxidized nitrogen and between 0.7 and 2.2mg/L phosphate-phosphorus, exceeding both NO_3-N and phosphorous thresholds (Taylor et al., 2006). Several other studies have investigated usage and nutrient losses from container nurseries (Colangelo and Brand, 2001; Mangiafico et al., 2008 and 2009; Wilson et al., 2010). Wilson et al. (2010) attempted to provide a regional estimate of water loss and nutrient runoff loads using data from a survey conducted on two Florida nurseries. Nursery water loss was between 12,391 and 88,982 L/ha per irrigation event, with NO_3-N losses of 1.9 to 10.1 kg/ha per event. Losses ranged from 19% to 68% of applied nitrogen. They further calculated that such losses could equate to as much as 525.2 kg/ha of wasted nitrogen.

One way larger nurseries have tried to reduce water usage and runoff losses is through use of retention ponds. If all runoff is kept and re-circulated, the problems associated with chemical leaching are contained, provided the pond is adequately lined. However, retention ponds have drawbacks as they may harbor diseases, and the cost associated with pumping and filtering from the pond may be too high to present a worthy solution to many smaller growers (Meadows, 2007).

Economics

Ornamental plant production has been cited as the most intensive form of agriculture (Reed, 1996). Since high quality plants are essential for sales, growers often over-apply water, fertilizers, and pesticides. Applications of high rates and frequency of inputs can increase production costs of ornamental plants (Wilson et al., 2010). Furthermore, the variety of species and container sizes present at most nurseries makes it especially difficult to efficiently apply water and chemicals without raising production costs (Zhu, Frantz, Derksen, and Krause, 2007). With the recent economic downturn, all growers will have to face higher material cost and

reduced sales returns. In addition, the demand for smaller, cheaper plants is on the rise, and customers are expected to buy fewer of the larger, more expensive trees and shrubs (J. Trimmer, Asst. manager/grower, New Nurseries Alvin Tree Farm, Alvin, TX, personal communication, September 6, 2011). Therefore, finding affordable ways to reduce wasted materials without compromising plant quality is especially important for the large-container grower.

Improving Irrigation Application Efficiency

Increasing water application efficiency (WAE) has been the focus of much of the research on improving irrigation efficiency. WAE is defined as water retained by the substrate divided by the water applied (Weatherspoon & Harrell, 1980; Haman, Smajstrla, and Pitts, 1996; Fain, Tilt, Gilliam, Ponder, and Sibley, 1998; Ruter, 1998). The most commonly used irrigation method in southeastern U.S. container production is overhead (Beeson & Knox, 1991; Fare, Gilliam, and Keever, 1992). Most water wastage occurs because water falls between the containers and not on the substrate surface. Because nurseries usually contain a variety of species and container sizes, overhead is usually the most practical method of water application (Beeson & Knox, 1991). Overhead irrigation is seldom used with larger containers because evaporative losses, wide container spacing, and canopy retention further decrease efficiency (Weatherspoon & Harrell, 1980; Beeson & Knox, 1991; Fare et al., 1992).

Water application efficiency can be increased by lengthening the time allowed for water to infiltrate the micropores of the substrate (Warren and Bilderback, 2005). One way to achieve this is by using microirrigation, which slows the actual rate of water discharge. Most large container growers today use some form of microirrigation, which is defined as a low pressure irrigation system that delivers water close to or within the root zone (Haman et al., 1996). Microirrigation systems used in the container industry usually deliver water via drip-emitter or spray stake placed at the surface of the substrate. The cost of installing and maintaining a

microirrigation system is generally more expensive due to the variety of parts and labor needed. In addition, emitters can easily be clogged due to algae, salt buildup, or particulate matter in the irrigation water; therefore expensive filters and sanitation measures may be needed (Lieth, 1996). However, because of the precise placement of water in these systems, WAE is greatly increased (Haman et al., 1996; Weatherspoon & Harrell, 1980), and disease pressure is greatly reduced. The cost per hectare of installing a microirrigation system also decreases as container size increases (Haydu & Beeson, 1997). Water loss in this system is due to evaporation from the substrate surface and leaching from the bottom of the container.

Another method of increasing infiltration time is by dividing an irrigation event into multiple application cycles, so that the same irrigation volume is spread over a larger span of time. This practice is known as cyclic, or pulse irrigation, and is also often employed in container nurseries (Beeson and Haydu, 1995). It is based on the principle of time-averaged application rate (TAAR—the volume of irrigation divided by the time between cycles), the critical factor affecting substrate moisture content (Warren and Bilderback, 2005; Zur, 1976). Zur (1976) found that the equilibrium volumetric soil water content was the same for any TAAR, despite differences in nozzle flow-rate and number of cycles. This was further supported by studies performed by Lamack and Niemiera (1993), in which water application efficiency was the same whether a single volume was applied in two, three, or six cycles. The same study also found that the greatest increase in WAE (24% over continuous application) was achieved with the treatment having the lowest TAAR of 0.8-1.3mL/min.

When combined with cyclic irrigation, microirrigation can further increase WAE compared to overhead (Ruter, 1998; Weatherspoon and Harrell, 1980). The combination of the two systems allows enough time for water to fill the micropores of the substrate, thus increasing the amount of irrigation water retained. An investigation by Kabashima (1993) found that one

California nursery was able to reduce annual water usage by 46% by combining both drip and cyclic irrigation. In California, where water prices are higher, this translates to a savings of tens of thousands of dollars per year. Ruter (1998) demonstrated that leaching volumes could be reduced by half by using cyclic microirrigation as opposed to once-daily irrigation. Better saturation resulting from cyclic microirrigation may also reduce water stress. Several studies have shown that plant growth is faster and of higher quality when cyclic microirrigation is used (Beeson, 1992; Beeson & Haydu, 1995; Beeson & Keller, 2003; Fain et al., 1998; Ruter, 1998; Thaxton, 2001). A cyclic irrigation regimen increased the growth index of an azalea crop by 65% compared with a single irrigation application (Beeson, 1992). Reduced leaching also translates to reduced nutrient waste. In a study performed by Fain et al. (1998), cyclically irrigated trees had at least 82% less total nitrogen leached than trees receiving single daily irrigations.

Irrigation Scheduling and Water Use Efficiency

In addition to water application efficiency, researchers are also interested in maximizing water use efficiency (WUE), which is defined as the volume of water required to produce a certain increase in plant mass (Warren and Bilderback, 2002), or the volume of additional irrigation water applied divided by the increase in plant production (Haman et al., 1996). Water use efficiency can be improved by knowing proper irrigation timing and volume, a concept applied by irrigation scheduling (Thaxton, 2001; Sammons, 2008; Warren and Bilderback, 2004; Warren and Bilderback, 2005).

Timing of water application is important because daily fluctuations in environmental conditions affect the water stress and needs of plants. Many growers follow best management practices that recommend irrigation should be applied only during the early dawn hours to reduce water lost to evaporation; however, it may often be overlooked that this recommendation is for overhead application only (Yeager et al., 1997). Studies have shown that midday and PM

irrigations reduce heat and water stress and therefore increase growth (Beeson, 1992; Warren and Bilderback, 2002 and 2004; Ruter, 1998). In an experiment conducted on spray-stake-irrigated *Cotoneaster dammeri*, increases of 57% and 69% in total dry weight, and 17% and 33% in water use efficiency were found in treatments irrigated midday and PM as compared to early morning (Warren and Bilderback, 2002 and 2004). Maximum container temperatures were also generally lower by 2-3°C, which was believed to aid stomatal conductance and growth. Ruter (1998) found a 40% increase in shoot dry weight in plants cyclically irrigated throughout the day as opposed to a single dawn application.

Evapotranspiration (ET) modeling is one way of determining irrigation timing. This approach allows the actual ET of a crop to be estimated by measuring ET based on environmental parameters and adjusting it with a specific crop coefficient (Beeson, 2005). The process of determining these coefficients is by regressing the ET of a specific crop to the ET of a reference crop, and modeling this relationship against a crop-specific parameter, such as time since transplant. This relationship can vary considerably within a species if such parameters vary; therefore, finding universal crop coefficients for container-grown woody ornamentals has proven difficult. Schuch and Burger (1997) modeled crop coefficients for common woody ornamentals in 3.8L containers based on time since transplant, and found that models varied due to microclimate and time of the year. Another coefficient model was developed for *Ligustrum japonicum* based on canopy closure that was independent of growth rate; however, it would require periodic measurement of plant canopy for each species (Beeson, 2005). In general, the current lack of universal, reliable models for many ornamental species and the expertise needed to use such a system makes ET-modeling currently impractical for most nursery operations.

Irrigation timing can also be determined by monitoring containers gravimetrically and irrigating based on percentage of container capacity. Container capacity is defined as the

proportion of substrate volume filled with water after saturation followed by drainage, and is the maximum amount of water a substrate-filled container can hold against gravity (Fonteno, 1996). Few studies report that better growth is attained when 100% of container capacity is replaced (Sammons and Struve, 2008; Beeson, 1992). Other studies have found that plant growth can be maximized by replacing only a portion of container capacity, a concept known as management allowed deficit (MAD). In this approach, the amount of plant-available water is determined gravimetrically by subtracting the container weight at wilting point from the weight of a potted plant at container capacity (Fonteno, 1996). Welsh and Zajicek (1993) found that plant growth in 3.8L *Photinia* was maximized when irrigated at a 25% deficit. Similarly, Beeson (2006) found optimum growth when woody ornamentals in 11.4L containers were irrigated at deficits of 20-40%, supporting the idea that over-watering container plants is detrimental to plant growth. Unfortunately, little research has been done on MAD and larger containers. Sammons and Struve (2008) developed a computer-controlled irrigation system that initiated and ended irrigation events based upon weight changes in 54.5L *Taxodium distichum*. Indicator trees were placed upon balances connected to a computer that logged their weights daily and managed irrigation so that container weights were within the target range corresponding to a specified percentage of container capacity. The system proved effective and reliable, but due to increased plant mass and root penetration, container capacity weights had to be periodically recalibrated.

Monitoring of substrate moisture content has also made irrigation timing possible through the use of tensiometers and electric probes. Thaxton (2001) compared growth, effluent volume, and nutrient uptake for trees irrigated using a switching tensiometer control system compared to cyclically timed treatments. Tensiometers were set to switch at certain moisture tensions, which signaled the computer system that controlled irrigation. Electric probes have also been used in a similar fashion. Nemali and van Iersel (2006) used dielectric moisture probes embedded in

container substrate to monitor substrate moisture content every 20 minutes. A datalogger was used to measure sensor output and control irrigation so that a specific moisture level was maintained constantly. Furthermore, this system worked independently of increases in plant mass and root penetration into the substrate. Murray and Lea-Cox (2004) had similar success using a time-domain-reflectometry system consisting of 18cm probes and a datalogger. These methods give accurate measurements of substrate moisture content; however, calibration is needed for specific substrates for increased accuracy. In addition, substrate moisture is not uniform throughout the container; therefore, if a correlation with container capacity is desired, multiple probes must be used and/or calibrated for container size as well. Because of the high cost generally associated with these systems, they are also impractical for commercial application.

The last method of controlling irrigation timing is monitoring of leachate, or container effluent. In such a system, a precipitation gauge or moisture sensor can be placed beneath the container to sense the presence of effluent, and relay that signal to a datalogger or other controlling device. In one study, a computer-controlled drip irrigation system was based on presence of effluent by suspending containers above a moisture sensor connected to a datalogger (Gonzalez, Struve, and Brown, 1992). The datalogger controlled irrigation valves so that upon leaching, solenoids could immediately be closed. In these systems, total effluent can be collected and measured to determine application efficiency. Precipitation gauges provide the benefit of measuring effluent volume during leaching, which may allow for predictive control of specific leach volumes, adding precision to a practice that has historically been rather ambiguous.

Leaching in the Container Industry

To reduce labor costs during container production, growers often apply fertilizers in fewer, larger doses as controlled release fertilizers (CRFs) (J. Trimmer, Asst. manager/grower, New Nurseries Alvin Tree Farm, Alvin, TX personal communication, December 30, 2011). If

CRFs break down at rates quicker than plant uptake, as is often the case, negative effects on the salinity in the container can result, especially when the above methods are used to reduce irrigation application volumes. Substrate salinity may rise to toxic levels, which can only be relieved by leaching (Bunt, 1988). Consequently, at least some leaching is generally recommended in container production.

Leaching fraction (LF) has historically been described in Best Management Practices as the volume of container effluent divided by the volume of water applied, and is intended to help growers apply adequate, but not excessive, irrigation (Yeager et al., 1997). When implemented, the use of leaching fraction has lessened the amount of wasted water and nutrients. Studies have shown that total nutrient loads lost are lower with reduced leach fractions. Tyler, Warren, and Bilderback (1996) reduced cumulative nutrient contents by 66%, 62%, and 57% for nitrate, ammonium, and phosphorus, respectively, when reducing leach fraction by about 20%. Although reduction of leaching fraction was found to have little or no effect on plant growth, Ku and Hershey (1991) found that it does alter pH and EC, which is important for salt-sensitive species, and in production situations where irrigation water is particularly saline. Sammons (2008) found that management of near-zero leach fraction increased WUE over 100% compared to 20% leach fraction; however, plant growth was compromised by 14%.

Despite the benefits of its use, general recommendations on leaching fraction for container crops have had little consensus. The BMP manual of container-grown crops advises against leaching more than 25% of applied water (Yeager et al., 1997). Leaching fractions of 10 to 15% have been recommended elsewhere as well, and it is not unusual for LFs of 40 to 50% to occur in industry (Reed, 1996; Zhu, 2007). Furthermore, growers often do not monitor or utilize leaching fraction in the first place, due to lack of equipment or expertise needed to do so. There is little standardization of methods for controlling leaching fraction commercially and in research

procedures, especially for larger, canyard-size crops. Most research on leaching fraction thus far has been performed on small greenhouse crops. Several factors influence the rate at which water passes through the container profile, including substrate composition, moisture content, container size, and root presence. Thus, significant delays may occur between the time irrigation is turned off and the time that leaching actually stops, making specific target leaching fractions difficult to achieve. The system used by Gonzales et al. (1992) turned off irrigation as soon as effluent occurred; however, total effluent still resulted in an 80% leaching fraction. Leaching fraction has been somewhat successfully achieved when using gravimetry to apply water based on daily water loss, or evapotranspiration (Graves, Anfinson, and Lappegard, 1995; Ku and Hershey, 1991 and 1992; Tyler et al., 1996). Actual leaching fractions using these methods were close to predicted leaching fractions, but in some cases were much lower, possibly due to plant biomass increase (Ku and Hershey, 1991; Graves et al., 1995). Still others have used small incremental additions of irrigation water (Yelanich and Biernbaum, 1993) or calibration with microtensiometers (Lang and Pannkuk, 1998) to achieve a targeted leaching fraction. While capable of curtailing water use and nutrient wastage, these methods are not practical for use on a typical growing operation. In order for more conservative leaching practices to be widely implemented in the commercial industry, simpler equipment and procedures are needed for growers to use.

Tipping Bucket Sensors

Tipping bucket rain gauges, or tipping bucket sensors, are relatively inexpensive devices that have been used in previous studies to measure field runoff (Barfield and Hirschi, 1986; Zhao, Dorsey, Gupta, Moncrief, and Huggins, 2001). It has rarely been observed to monitor container nursery leaching (Zhu, Krause, Derksen, Brazee, Zondag, and Fausey, 2004a). The device typically consists of a cylindrical catchment dome that collects water and funnels it into a

steady stream into a receiving tray located directly below, inside the dome. The triangular receiving tray is divided into two equal collection areas, and is centered on a pivot so that it tips to expose only one collection area to the stream at a time. Once a certain volume of water has collected on one side, the tray tips to expose the opposite side to the stream, and empties the collected water into a drainage grate in the bottom of the device. Attached to the center of the tray is a downward-facing plastic arm equipped with a small magnet. A few millimeters in front of the magnet is a magnetic reed switch (an open circuit). Upon each tip of the receiving tray, the magnet passes across the length of the switch, briefly closing the circuit, so that a pulse is sent to either a battery operated counter or datalogging device. The total volume of runoff can easily be calculated by multiplying the volume per tip by the number of tips. However, the volume per tip is not a constant value, but is dependent upon flow rate into the receiving tray, and must therefore be calibrated (Barfield and Hirschi, 1986; Edwards, Jackson, and Fleming, 1974; Marsalek, 1981). This can easily be done by logging the time it takes for one tip, S, at constant flow rate, R, so that: volume = RS. This should be repeated for several different flow rates, including minimum and maximum rates expected to be encountered. Volume per tip and time per tip can then be plotted, and a curve fitting technique can be used to generate a calibration function (Zhao et al., 2001).

Such devices have been used to monitor runoff from pot-in-pot nursery sites, but not for control of irrigation systems (Zhu et al., 2004a, 2004b). Since the reduction of leaching volumes can increase water application efficiency and reduce nutrient runoff, its use as an irrigation control method may be beneficial if a predictable relationship between the initial volume of effluent at irrigation shut off and total volume of effluent after drainage can be determined.

Quantifying Container Effluent

The ability of irrigation water to flush salts from the substrate depends on the salinity of the irrigation water, the percolation rate of the substrate, the conductivity of the substrate, and the volume of water that passes through the profile. The salinity of irrigation water affects the ability of substrate solutes to diffuse from high concentrations in the container to low concentrations in the irrigation water. The percolation rate affects how much time the irrigation water spends mixing with the substrate solution, and depends on the application rate as well as the physical properties of the substrate. Longer rates lead to more intimate mixing, and thus more removal of salts from the profile. Substrate conductivity affects how thoroughly the soil profile is wetted, and is affected by substrate physical properties as well as moisture content. Only substrate that is wetted can be leached. Better conductivity will allow more lateral movement of water and more thorough wetting of substrate. Lastly, higher volumes of water passing through the substrate can carry away larger amounts of solutes. Kerr and Hanan (1985) leached columns of substrates that had differing textures (differing percolation rates) with solutions of differing salinities and measured the change in effluent electrical conductivity. The greatest changes in effluent salinity occurred within the first container capacity leached, and slower percolation rates led to greater efficiency of salt removal. Thus, it can be inferred that without changing the irrigation water salinity, water percolation rate, or conductivity of the substrate, continued leaching beyond a certain point has little to no effect on container salinity. Knowing this point would be very useful to growers so that gross over-irrigation can be avoided.

A single leaching fraction, since it is calculated based upon volume of water applied, can result in several different actual volumes leached, depending on the time it takes for water to pass through the container profile. Longer delays between irrigation shut-off and the end of leaching result from higher tortuosity in the paths followed by the irrigation water. In addition,

depending on the size of the container and the application rate of irrigation water, some leaching fractions may be difficult to achieve, as the volume needed to be leached increases as irrigation applied increases for any given leaching fraction. Kerr and Hanan (1985) suggested that leaching based upon the maximum volume of water held by a container of substrate (container capacity) would result in greater water use efficiency. Leaching based on the container capacity rather than the volume of applied water would result in consistent volumes for a single leaching target.

The ability to achieve a certain target leaching fraction depends on the time it takes for water to percolate through the substrate profile. As substrates dry out, hydrophobicity increases, limiting the amount of substrate that is actually wetted. Instead, water may funnel downwards in a limited path below the dripper (Kerr and Hanan, 1985), or simply slide off the bark particles and down the sides of the container (Beardsell and Nichols, 1982). Since leaching is important only for removing salts, inefficient leaching is simply a waste of water. Theoretically, substrates that are at a higher moisture content should provide more tortuous paths for water flow, allowing more substrate to be wetted, and more solutes to be carried away. Hanan, Olympios, and Pittas (1981) investigated the physical properties of several potting substrates and determined the rate of salt removal by leaching for each. They found increased percolation rates had decreased final moisture contents, and that percolation rates increased exponentially as the ratio of porosity to moisture content increased. Furthermore, they found that increased percolation rates correlated with high volumes needed to reduce effluent salinity. Therefore, it can be hypothesized that decreased moisture content of substrates correlate with increased percolation rates and perhaps decreased salt leaching effectiveness.

CHAPTER 2

COMPARISON OF TWO METHODS FOR CONTROLLING NURSERY CONTAINER EFFLUENT AND EVALUATION OF THEIR ACCURACIES ACROSS CONTAINER SIZE AND MOISTURE DEFICIT

Introduction

Leaching during nursery production is widely practiced to reduce high salt concentrations in substrates from excessive fertilizer application. To reduce labor inputs, nutrients are usually applied in less frequent, high-rate applications of controlled release fertilizers. When nutrients are released more quickly than plant uptake, substrate salinity may rise to toxic levels that can only be relieved by leaching (Bunt, 1988). Anticipated increases in environmental regulations and fertilizer costs will require changes in cultural production practices (Reed, 1996). Increasing fertilizer efficiency and reducing offsite nutrient movement associated with leaching practices are of particular concern for producers (Taylor et al., 2006; Wilson et al., 2010). Recent attention has focused on reducing leaching from nursery containers, which wastes both water and fertilizers. Typically growers are advised to irrigate to achieve a certain leaching fraction, which is defined as the volume of container effluent divided by the volume of applied irrigation.

$$Lf = \frac{Volume_{effluent}}{Volume_{applied}} \times 100$$

Reduction of leaching fractions has resulted in reduced total nutrient loads in nursery runoff (Tyler et al., 1996). Reducing leaching fractions had minimal or no effects on growth and quality of some crops (Ku and Hershey, 1991; Graves et al., 1995; Tyler et al., 1996) Leaching fraction recommendations typically range between 10 and 25%, however, due to the difficulty of measuring and achieving targeted leaching fractions, it is rarely measured (Yeager et al., 1997; Zhu, 2007). It is not unusual for leaching fractions of 40 to 50% or more to occur in commercial nurseries, with applied volumes possibly far-exceeding what is necessary to control salinity

(Reed, 1996). Limited research has been conducted to understand effluent volumes required to remove high salt concentrations (Kerr and Hanan,1985). Deciding when to turn off irrigation to reach specific leaching fractions is difficult under greenhouse or field conditions given the variability in water percolation rates due to substrate composition, moisture, container size, and root penetration. Fluctuations in effluent and irrigation application volumes increase the complexity of attaining a target leaching fraction, which has only been achieved using gravimetric monitoring (Ku and Hershey, 1991; Graves, et al., 1995; Tyler et al., 1996). Furthermore, these gravimetric systems are subject to error due to biomass increase (Ku and Hershey, 1991). In addition, leaching fraction, calculated as a function of application irrigation volume, does not quantitatively account for water volume percolating through the container profile. Using target leach volumes as a percentage of container capacity (PCC) may provide a simpler and more accurate measurement, allowing for more consistent accounting of water percolation and effluent volumes across varying container sizes and moisture deficits.

$$PCC = \frac{Volume_{effluent}}{Volume_{Cont.Capacity}} \times 100$$

Indicator plants have been used to provide moisture status via sensors to the irrigation system to improve irrigation efficiency (Nemali and van Iersel 2006; Gonzales et al., 1992; Murray and Lea-Cox 2004; Thaxton, 2001). Tipping bucket sensors placed beneath indicator nursery containers are easy to set-up and monitor (Zhu, 2004). The ability to use the initial effluent at irrigation shut-off (target) to predict the total volume leached (actual) may make tipping bucket sensors an effective water management and environmental tool for nursery irrigation, and would allow growers to apply specific volumes of water needed to control salinity. Increased substrate moisture may provide more tortuous paths for water flow, since drier substrates tend to become hydrophobic and limit the spread of water. Therefore, more thorough

wetting may increase salt-leaching effectiveness. The objectives of this study were to compare the accuracy of two leaching methods, leach fraction (LF) and percent of container capacity (PCC), to relate initial post-irrigation effluent to total effluent using tipping bucket sensors, and to determine the influence of container size and moisture deficit on each method. Also, the effects of antecedent substrate moisture levels on salt leaching effectiveness were determined.

Materials and Methods

Preparation of Substrate

Substrate was composed of pinebark screened to <15.9mm, amended with 0.59 kg N m^{-3}, 0.30 kg P m^{-3}, and 0.3 kg K m^{-3} (Sta-Green Corporation, St. Louis, MO). Containers of volumes 3.8L, 10.4L, and 20.7L were filled with substrate, with each container of the same volume receiving the same mass, compressed three times, and saturated to achieve uniform bulk density. Three known masses of moist substrate were oven-dried to determine percent dry-matter of substrate (Eq. 1). The oven-dry mass of each container was calculated by multiplying percent dry mass by the initial mass of container at potting (Eq. 2).

$$\%DW_1 = \frac{Mass_{oven-dry}}{Mass_{moist}} \qquad \text{(Eq. 1)}$$

$$Mass_{oven-dry} = \%DW_1 \times Mass_{initial} \qquad \text{(Eq. 2)}$$

A 100g sample of oven-dry substrate was passed through a series of 12 standard sieves (12.5, 9.5, 6.35, 3.35, 2.36, 2, 1.4, 1, 0.5, 0.25, 0.11, 0.05mm, and pan) and shaken for 3 minutes at 278 oscillations/minute in a Ro-Tap® shaker (W.S. Tyler Industrial Group, Mentor, OH). Contents from each sieve were weighed to determine particle size distribution.

Three containers per size class were measured for container capacity, pore space, and bulk density. Containers were lined with plastic bags, filled with substrate, and saturated. After two hours, each container was weighed before the plastic was punctured to allow gravitational

drainage of excess water. After one hour or when no visible water was exiting the containers, containers were re-weighed. Based on saturated, drained, and oven-dry masses, the following calculations were completed:

Air-filled porosity: $$f_a = \frac{(M_s - M_d) \times \rho_w}{V_t} \quad \text{(Eq. 3)}$$

where M_s is the saturated mass of the substrate, M_d is the drained mass of the substrate, ρ_w is the density of water, and V_t is the total volume of fill.

Container Capacity $$\mathrm{K} = M_d - M_{OD} \quad \text{(Eq. 4)}$$

where M_{OD} is the oven dry mass of the substrate, calculated by multiplying the percent dry matter times the mass of moist fill.

Bulk Density $$D_B = \frac{M_{OD}}{V_t} \quad \text{(Eq. 5)}$$

Containers were maintained under greenhouse conditions until start of experiment and were periodically weighed to maintain container moisture deficits of 0.05, 0.20, and 0.30 from container capacity. Container mass was used to calculate deficit according to equation 6.

$$Deficit = \frac{Mass_{container} - Mass_{OD}}{\mathrm{K}} \quad \text{(Eq. 6)}$$

Leaching Apparatus

A single leaching station consisted of stacked metal stands, each lined with a rubber drainage mat. A tipping-bucket sensor was positioned on the bottom stand, and a container was positioned over the top stand so that effluent could drain from the container into the tipping bucket sensor. The drain in the bottom mat was fitted with a plastic funnel to allow effluent to be collected from the tipping bucket sensor (Figure 1).

Leaching Simulations

Containers were weighed prior to simulations to determine true moisture deficit. Irrigation was applied at 2.19 mL s^{-1} via 360° spray stakes. Effluent volume data measured using tipping-bucket sensors were stored using a datalogger (CR23X, Campbell Scientific, Logan, UT)

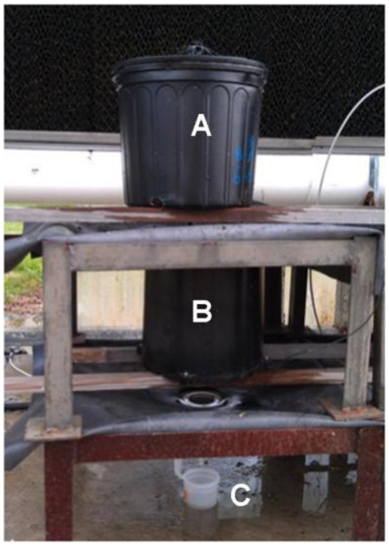

Figure 1. Leaching apparatus used for simulation experiments in 2012. A) Substrate-filled container. B) Tipping bucket sensor. C) Effluent collection cup.

(Figure 2) and included the duration of each irrigation application, volume to initiate leaching, and effluent volume. The logger calculated volume of water applied by multiplying seconds

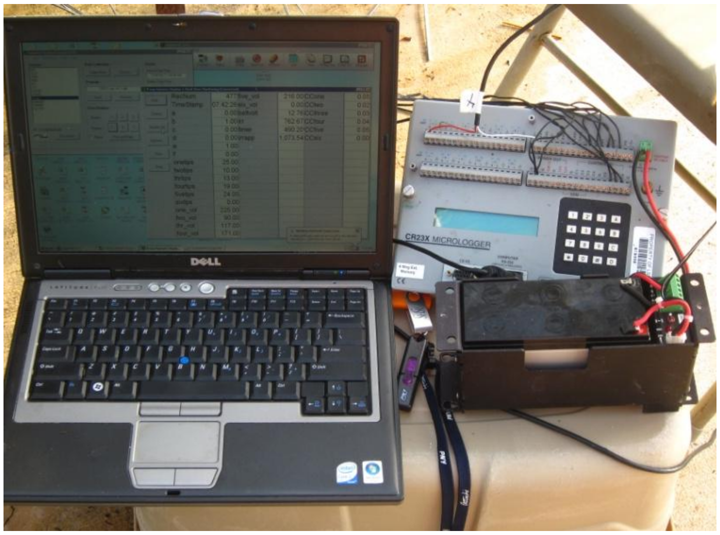

Figure 2. Campbell Scientific CR23X datalogger and PC computer system used to monitor leaching fraction during leaching simulation experiment in 2012.

elapsed by application rate. Target leaching fractions (TLF) were calculated by dividing the volume leached at the end of irrigation by the volume applied (Eq. 7).

$$TLF = \frac{Volume_{leached_t}}{Volume_{applied}} \times 100 \qquad \text{(Eq. 7)}$$

Calculations were updated every five seconds and displayed on a computer screen during the simulation. Containers were irrigated until TLFs (0%, 20%, 40%, or 60%) were achieved. For 0%, irrigation was shut off at first drop of effluent. Effluent was measured until drainage ceased. Total effluent volume was divided by volume applied to determine actual leach fraction (ALF):

$$ALF = \frac{Volume_{leached_f}}{Volume_{applied}} \times 100 \qquad \text{(Eq. 8)}$$

Volume of effluent at the end of irrigation was divided by container capacity to determine target percent container capacity (TPCC) (Eq. 9).

$$TPCC = \frac{Volume_{leached_t}}{\mathrm{K}} \times 100 \qquad \text{(Eq. 9)}$$

Volume of total effluent after leaching was divided by container capacity to determine actual percent container capacity (APCC) (Eq. 10).

$$APCC = \frac{Volume_{leached_f}}{\mathrm{K}} \times 100 \qquad \text{(Eq. 10)}$$

Effluent was collected in a series of either 140-mL for 3.8L and 10.4L containers, or 240-mL for 20.7L containers. Smaller aliquots were taken on 3.8L containers to obtain a comparable quantity of effluent samples with the larger containers. Electrical conductivity and pH were measured using a portable EC meter (HI 98312, Hanna Instruments, Smithfield, RI) and pH electrode (EW-5992-02, Cole Parmer, Vernon Hills, IL), respectively.

Experimental Design

The experiment included three container sizes, three moisture deficits, and four TLFs. Each TLF contained three replications, for a total of 108 simulations, arranged in a 3x3x4x3 factorial design.

Validation

To validate the method proposed, the experiment was repeated with irrigation terminated for the target percent of container capacity (TPCC) 0%, 10%, 30%, and 50%. For 0%, irrigation was turned off at the first drop of effluent. TPCCs were calculated by dividing the volume leached at the end of irrigation by the container capacity (K) (Eq. 9). Containers were monitored until drainage ceased. Total volume leached was divided by container capacity (K) to determine APCC (Eq. 10). Samples of effluent were not taken.

Statistical Methods

Linear regression models were fitted in SAS (Version 9.1, SAS Institute, Cary, NC) using the regression procedure for ALF and APCC with fixed model parameters of TLF and TPCC, respectively, container size, and moisture deficit. Analysis of variance statistics (R^2 and MSE) were compared between the combined and individual model parameters to determine each parameter's significance to the model. Pearson's correlation coefficients were calculated using the correlation procedure to determine the correlation between model parameters. Fisher's Least Significant Difference was compared between the two calculations to determine the sensitivity of parameters.

Results

Substrate Physical Properties

Coarse-textured particles accounted for 69.25% of substrate dry weight, with medium and fine-textured particles accounting for 23.48% and 7.26% of substrate dry weight,

respectively (Table 1). Substrate and physical properties by container size are consistent with best management guidelines for irrigated container substrates (Table 2) (Yeager et al., 2007).

Table 1. Particle size distribution of 15.9mm-screened pinebark used for leaching simulation experiment in spring 2012.

U.S. standard sieve no.	Sieve opening (mm)	Percent composition (%)[a]
1/2	12.50	3.77
3/8	9.50	5.54
1/4	6.35	14.97
6	3.35	27.81
8	2.36	12.88
10	2.00	4.28
14	1.4	8.88
18	1.00	6.24
35	0.50	8.36
60	0.25	4.03
140	0.11	1.88
270	0.05	0.68
Pan	0.00	0.67
Texture[b]	Coarse	69.25
	Medium	23.48
	Fine	7.26

[a]Values averaged from three oven-dried samples.
[b]Texture grouping: coarse > 2.0mm; medium > 0.5mm and <2.0mm; fine < 0.5mm

Table 2. Substrate physical properties (air-filled porosity (f_a), container capacity (K), moisture deficit at container capacity ($\theta_{(K)}$), and bulk density (D_B)) in three container sizes for leaching simulation experiment in spring 2012.[a]

Container size	f_a	K (mL)	$\boldsymbol{\theta_{(K)}}$	$\mathbf{D_B}$ **(g cm^{-3})**
3.8L	0.702	1325	0.365	0.226
10.4L	0.714	3930	0.377	0.238
20.7L	0.724	7375	0.357	0.245

[a]Averaged over three replications.

Leaching Amounts

Actual volumes applied at the start of leaching did not differ in smaller containers; however, as container size increased, leaching occurred sooner, with less applied water at higher moisture deficits (Figure 3).

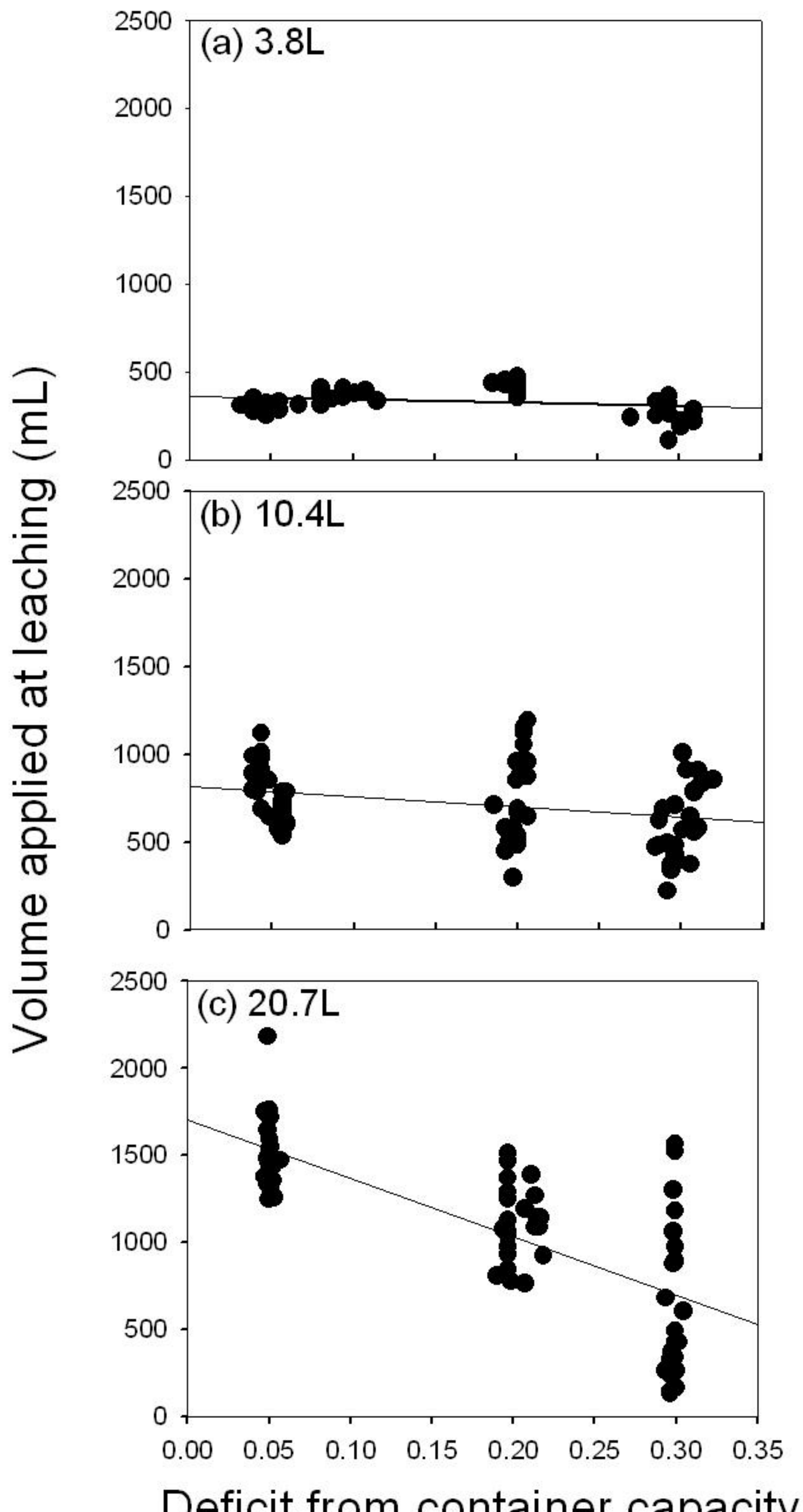

Figure 3. Volume of irrigation water applied at the start of leaching for (a) 3.8L, (b) 10.4, and (c) 20.7L containers and at approximately 5%, 20%, and 30% moisture deficits from container capacity. Includes data from both first and validation experiments.

In all container sizes, a larger fraction of the deficit was replaced before the start of leaching in containers with higher antecedent moisture levels than in containers with lower antecedent moisture levels (Figure 4). For example, in containers having a 0.30 moisture deficit, all containers began leaching at or below 100% deficit replacement, whereas all containers at a 0.05 moisture deficit began leaching after reaching a 200% deficit replacement. Higher ALFs did not result in higher effluent volumes, as total effluent volumes varied greatly with actual leaching fraction (Figure 5).

Linear Regressions

Across all container sizes, decreasing water deficits increased ALF per TLF, while increasing TLFs led to less ALF variation across water deficits (Figure 6). When ALF was regressed to TLF without accounting for deficit and container size, a poor correlation was found (R^2=0.3105). Accounting for deficit and container size in the regression greatly increased its accuracy (R^2=0.7341) (Figure 6). Container size and moisture deficit had significant effects on the relationship between actual and target leaching fractions ($p<0.05$) (Table 3). The effects of moisture deficit diminished as target leach fraction was increased. The effects of moisture deficit and size became more muted as container size increased (Figure 6). The same data was used to recalculate TPCC and APCC in the first experiment. When APCC was regressed to TPCC, the relationship without considering moisture deficit and container size was highly accurate

Table 3. Parameter estimates[a] of actual leaching fractions regressed to target leaching fractions in first leaching simulation experiment in spring 2012 on substrate-filled pots.

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|[b]
Intercept	**1**	0.66154	0.02513	26.33	<.0001
Container size	**1**	-0.01546	0.00353	-4.38	<.0001
Moisture deficit	**1**	-1.03724	0.08569	-12.10	<.0001
TLF	**1**	0.43391	0.03937	11.02	<.0001

[a]Estimates found using PROC REG in SAS 9.1 (Cary, NC).
[b]p=0.05

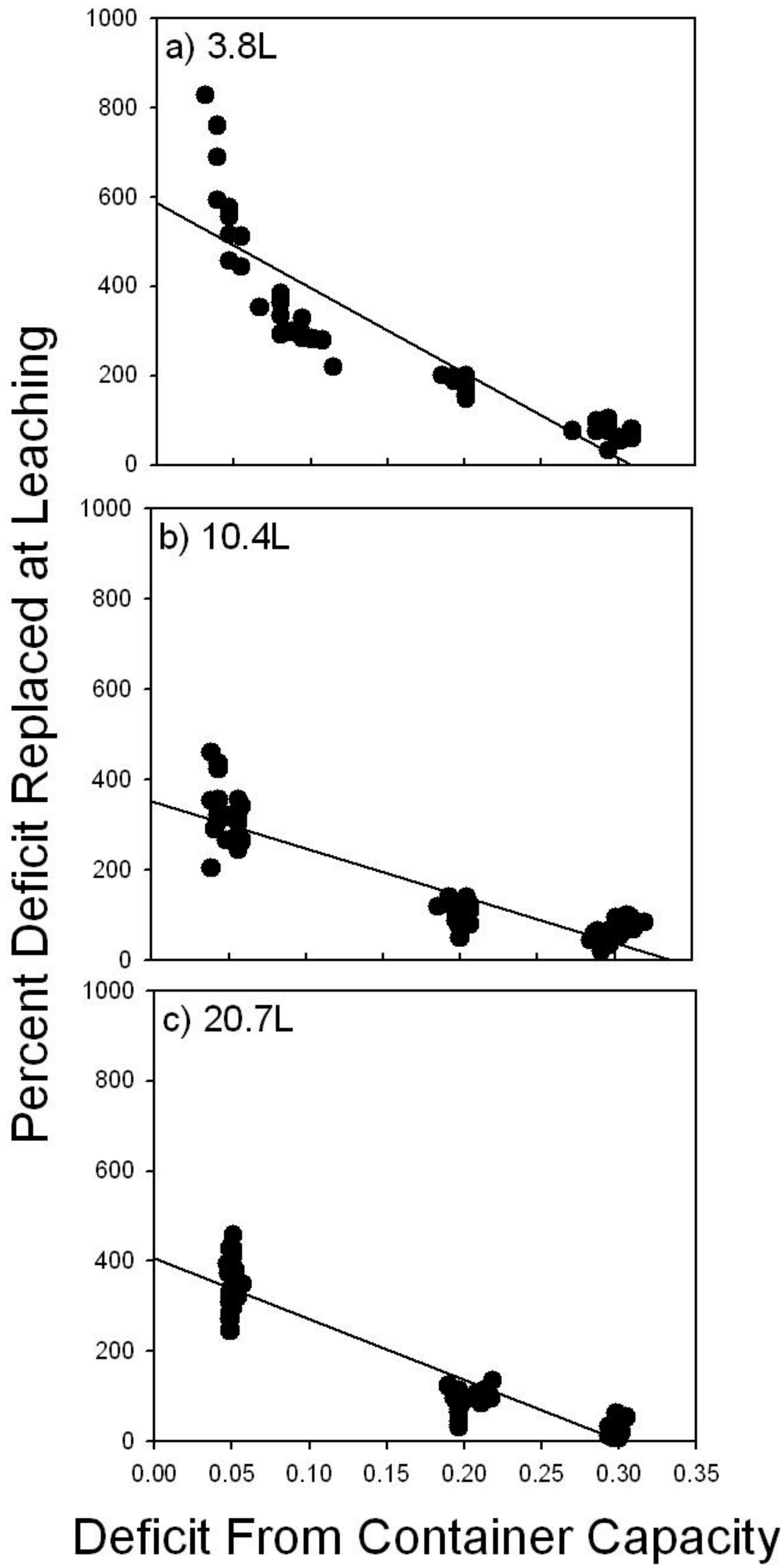

Figure 4. Fraction of moisture deficit (from container capacity) replaced by irrigation at the start of leaching for (a) 3.8L, (b) 10.4, and (c) 20.7L containers and at 5%, 20%, and 30% moisture deficits from container capacity from first and validation experiments.

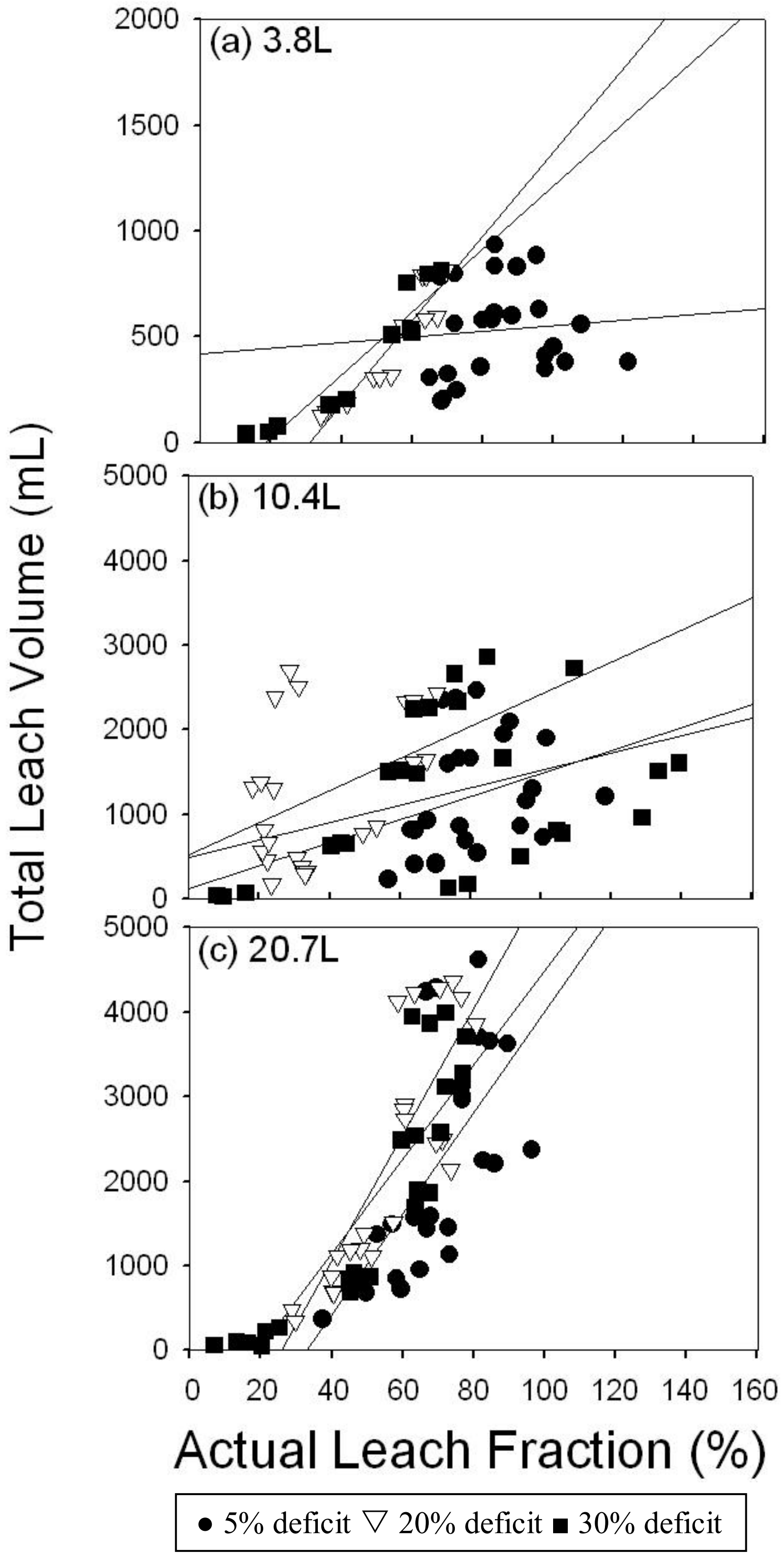

Figure 5. Total leach volumes resulting from ending irrigations at specified target leaching fractions in (a) 3.8L, (b) 10.4L, and (c) 20.7L containers at 5%, 20%, and 30% deficits from container capacity. Includes data from first and validation experiments.

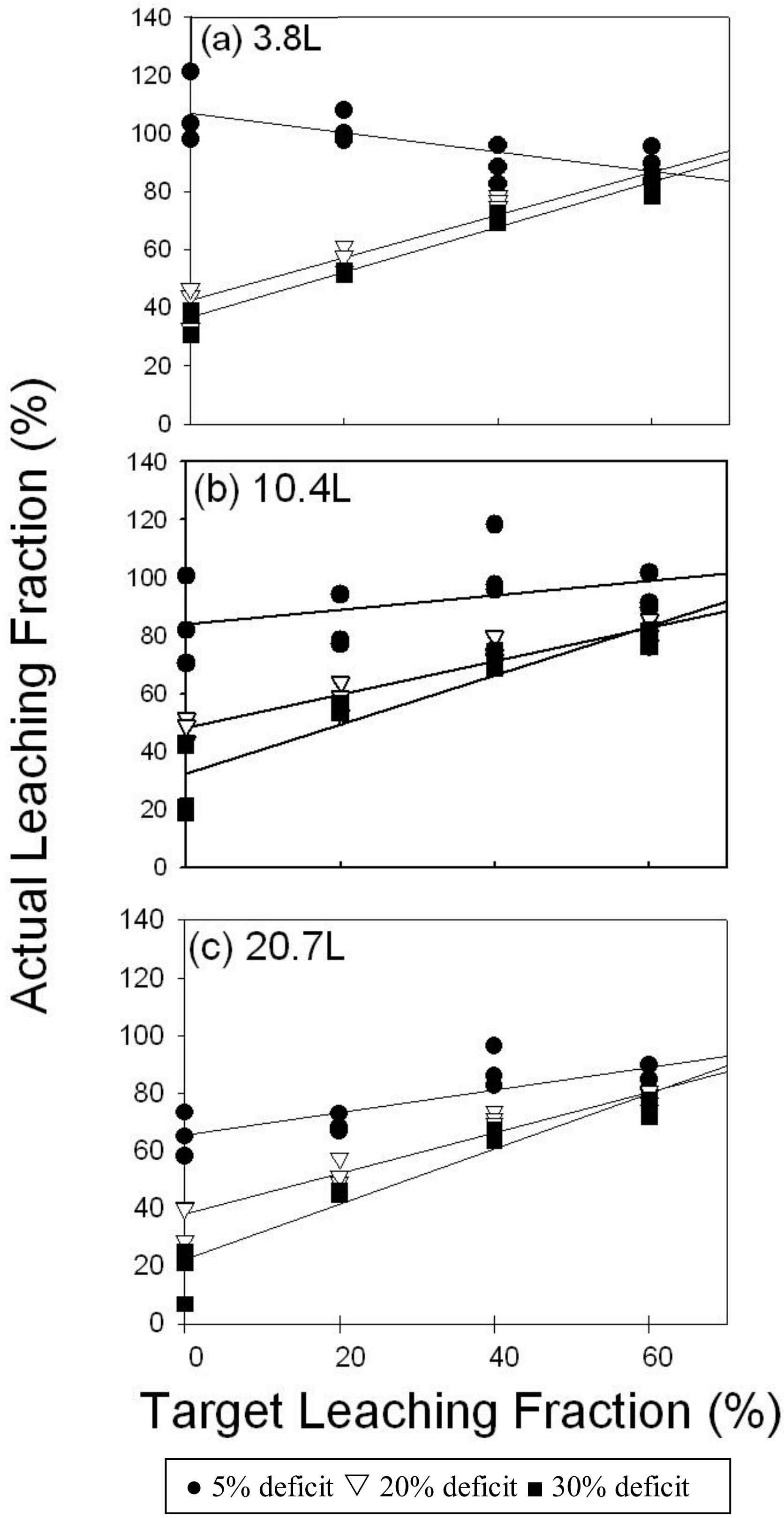

Figure 6. Actual leaching fractions resulting from ending irrigations at specified target leaching fractions in (a) 3.8L, (b) 10.4L, and (c) 20.7L containers at 5%, 20%, and 30% deficits from container capacity in first experiment.

(R^2=0.9266). Accounting for deficit and container size added some accuracy (R^2=0.9713) (Figure 7). When APCC was regressed to TPCC in the validation experiment, similar results were found (R^2=0.9523 without deficit and container size, R^2=0.9839 with) (Figure 8). As in the first experiment, where ALF was regressed to TLF, container size and moisture deficit also had significant effects on the regression ($p<0.05$) (Table 4). However, the comparative Fisher's least significant differences for ALF vs. TLF and APCC vs. TPCC were 0.125 and 0.040, respectively, more than 3 times less for the latter model. Variation in the data due to error (MSE) were 0.02 and 0.002 for leach fraction and percent of container capacity, respectively (Table 5). Despite the effects of container size and moisture deficit, APCC's were consistently approximately 10% greater than their TPCC.

Table 4. Parameter estimates[a] of actual percent of container capacity leached regressed to target percent of container capacity leached in validation simulation experiment in spring 2012 on substrate-filled pots.

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|[b]
Intercept	**1**	0.17462	0.00757	23.07	<.0001
Container size	**1**	-0.01127	0.00109	-10.31	<.0001
Moisture deficit	**1**	-0.26178	0.02652	-9.87	<.0001
TPCC	**1**	1.11176	0.01419	78.36	<.0001

[a]Estimates found using PROC REG in SAS 9.1 (Cary, NC).
[b]p=0.05

Salt Leaching

For simplicity, electrical conductivity data is shown for the 40% and 60% TLFs. Higher moisture deficits did not result in higher initial EC. All containers showed a decrease in EC throughout the leaching process, and antecedent substrate moisture content did not affect the rate of decrease in EC (Figure 9). Most leaching curves showed a gradual decrease followed by a slight increase towards the end of leaching. More rapid decreases were seen in containers with higher initial EC readings (>3 mS).

Table 5. Analysis of variance for regression of actual and target leaching fractions and actual and target percent of container capacities, without accounting for container size and moisture deficit, in leaching simulation experiment in 2012.

First Experiment - ALF vs. TLF					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	1.01669	1.01669	47.73	<.0001
Error	106	2.25782	0.02130		
Corrected Total	107	3.27451			
Validation Experiment – APCC vs. TPCC					
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	4.92243	4.92243	2114.23	<.0001
Error	106	0.24679	0.00233		
Corrected Total	107	5.16922			

Discussion

Using TLF to control leaching for salt removal during nursery container production requires measurement of container size and substrate moisture content, or substrate saturation prior to implementing leaching protocols. Based on the results from the presented data, as substrate moisture approaches saturation, lower leaching fractions were more difficult to achieve across all container sizes evaluated. The effect of substrate moisture content is most likely associated with the water absorbency characteristics of the substrate. Increased water absorbance of the substrate occurred at higher moisture contents. Higher antecedent substrate moisture content allows improved pore connectivity and reduces hydraulic conductivity for greater water retention (Cannavo, Hafdhi, and Michel, 2011). When water percolation slows, lower leaching fractions can only be achieved by terminating irrigation prior to the initiation of leaching from the container. On the other hand, drier substrates are difficult to rewet (Airhart, Natarella, and Pokorny, 1978; Beardsell and Nichols, 1979), and tend to funnel water through the profile in paths with less horizontal movement (Hanan et al., 1981), or water simply passes down

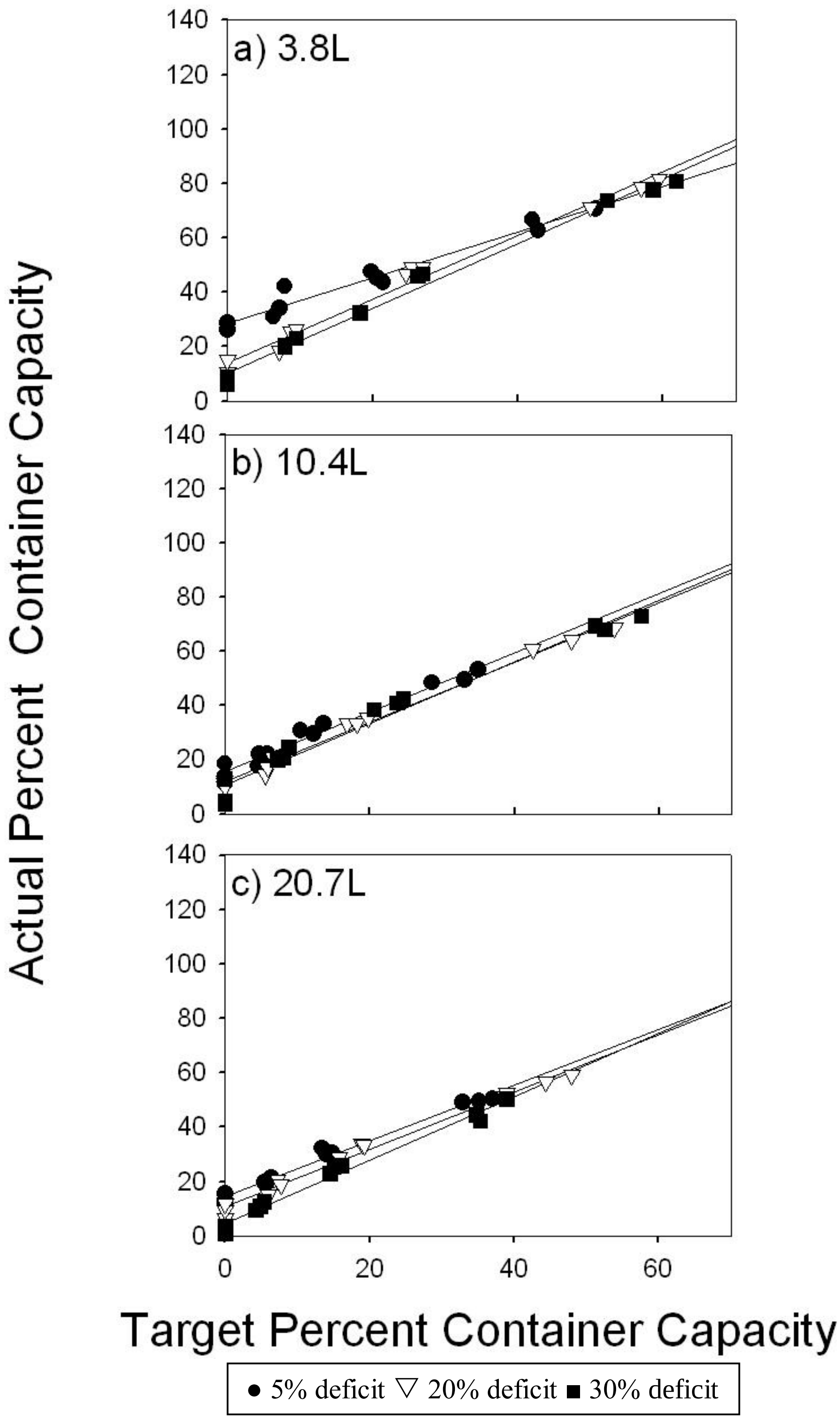

Figure 7. Actual percent of container capacities leached after ending irrigations at specified target percent of container capacity leached in (a) 3.8L, (b) 10.4L, and (c) 20.7L containers at 5%, 20%, and 30% deficits from container capacity in first experiment.

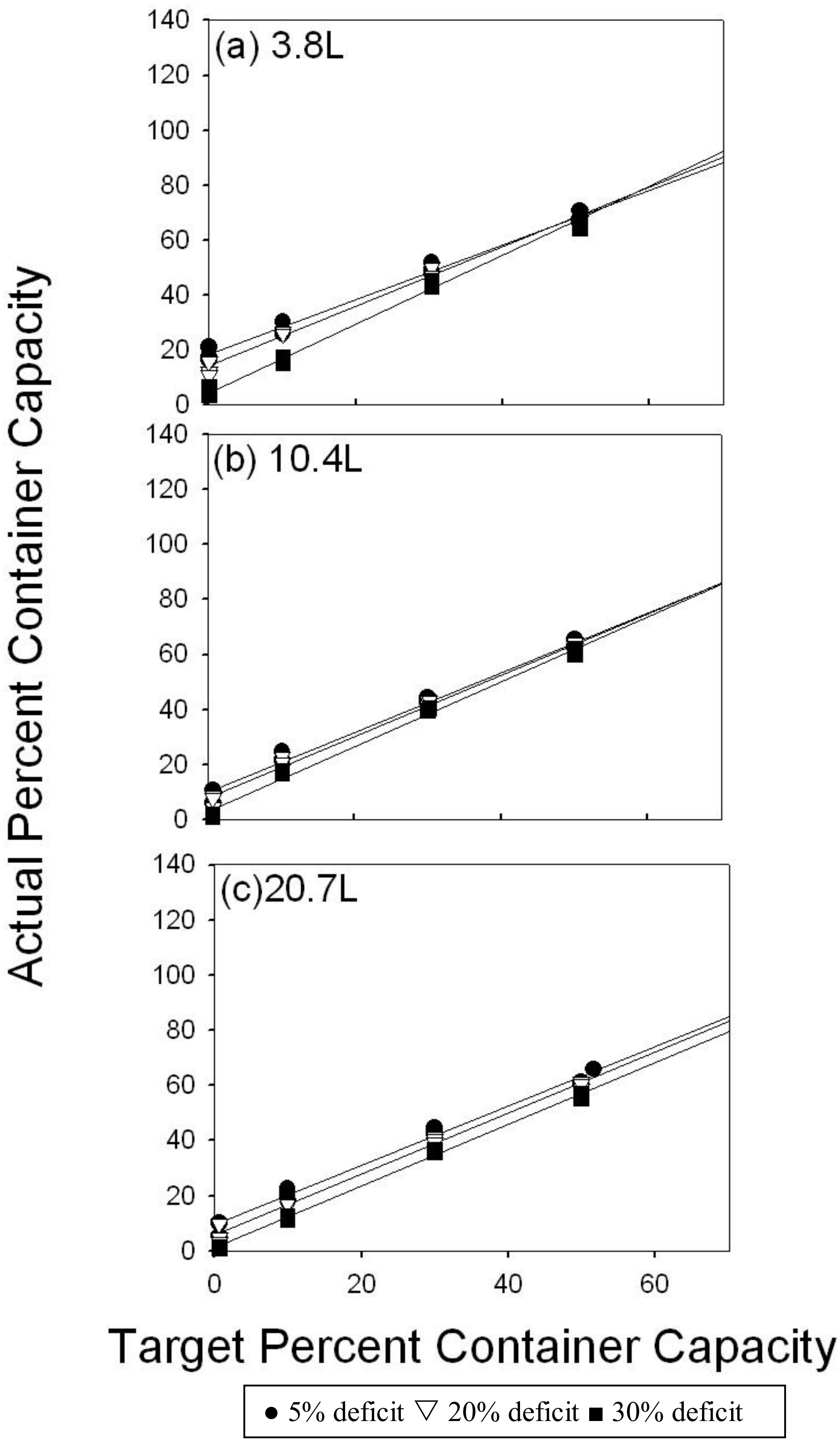

Figure 8. Actual percent of container capacities leached after ending irrigations at specified target percent of container capacity leached in (a) 3.8L, (b) 10.4L, and (c) 20.7L containers at 5%, 20%, and 30% deficits from container capacity in validation experiment.

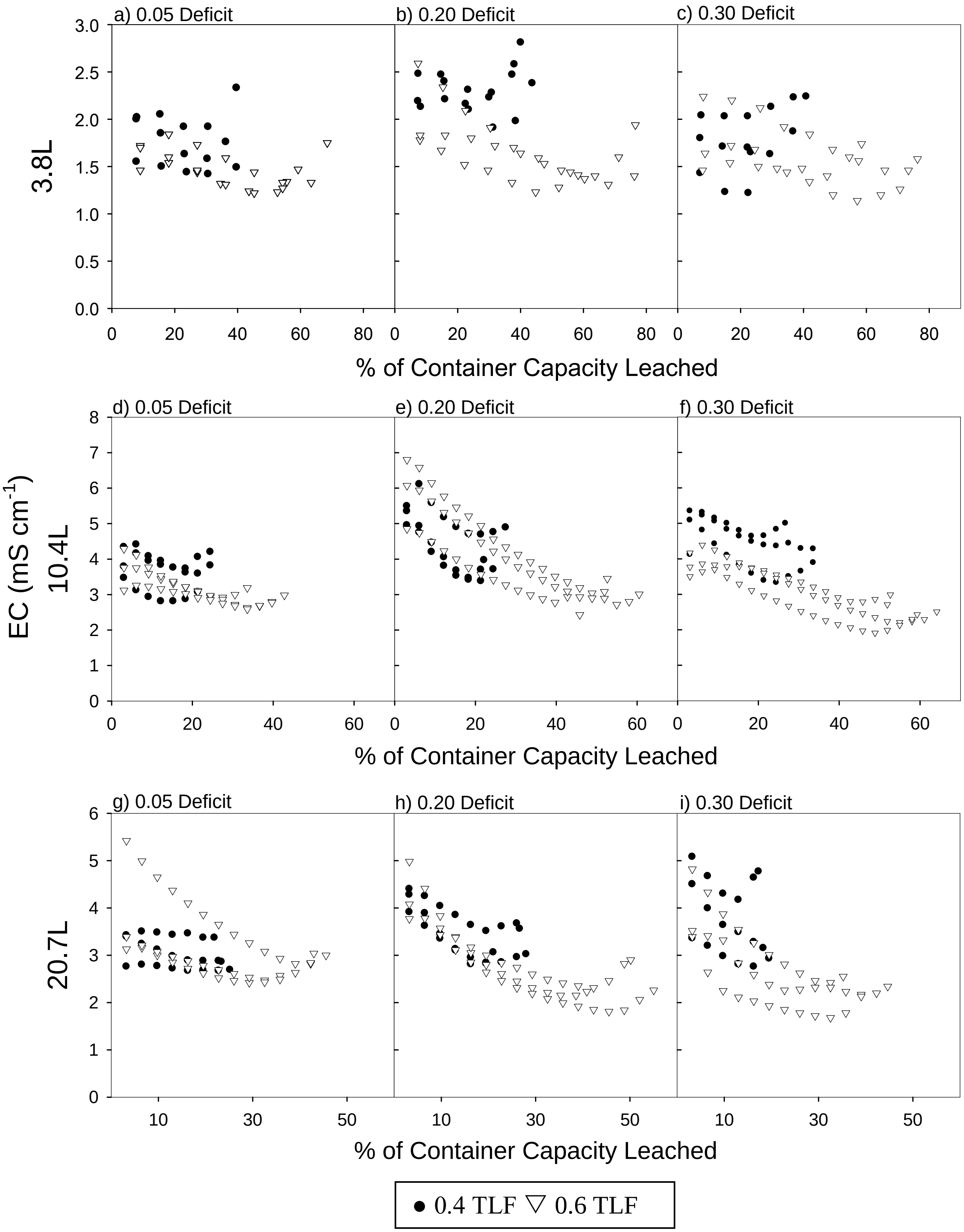

Figure 9. Electrical conductivity (mS cm^{-3}) of effluent sampled at increasing proportions of container capacity leached in 3.8L, 10.4L, and 20.7L containers at 5%, 20%, and 30% deficit from container capacity. Individual replications are shown.

the sides of the container, leaving the bulk of the substrate un-wetted. In this experiment, the decrease in volume applied to initiate leaching in larger containers at higher deficits (Figure 3) is probably due to the decreased proportion of substrate covered by the sprinkler head coupled with decreased horizontal water movement within the substrate.

Since many growers do not employ instruments to monitor moisture deficits, leaving substrate moisture content unaccounted for can lead to imprecise implementation of irrigation and effluent volumes when using the LF method. For example, when correlating volume of applied irrigation to ALFs (Figure 5), a single applied volume resulted in leaching fractions of 30 to 120% in 10.4L containers, depending on the moisture deficit. In 20.7L containers, the same volume applied to achieve a 0% TLF resulted in both 5% and 75% leaching fractions. This only emphasizes the disconnect between TLF and water volumes necessary to achieve TLFs. Data presented from this experiment show lowering leaching fractions did not necessarily equate to a more conservative practice than using higher leaching fractions. Higher target leaching fractions resulted in a convergence of actual leaching fractions, suggesting that the TLF protocol may be appropriate at TLF of 60% or higher. However, a 60% TLF exceeds recommended TLF of 25% for commercial nursery production (Yeager et al., 1997).

A simpler alternative to TLF in controlling salt leaching and accounting for irrigation volumes during nursery container production would be the use of percent container capacity (PCC). As exhibited in the figures 7 and 8, TPCC vs APCC resulted in strong linear relationships (R^2=0.9266) compared to TLF vs ALF (R^2=0.3105). Although statistically, container size and moisture deficit had significant effects on both TLF and TPCC, based on the mean square error terms, the TPCC method decreased variance and increased measurement accuracy 814% compared to TLF. This increased level of measurement accuracy of water volumes based on container capacity increased the sensitivity of the method so that the effects of moisture deficient

and container size are statistically significant but not biologically significant. Furthermore, the use of the PCC method not only allows a more streamlined approach for salt removal from containers, but also provides a method to account for irrigation volume that could improve irrigation efficiency during container production.

The fact that all the treatments used in this study ceased irrigation after leaching was initiated is important, as not all containers initiated leaching at the same time (Figure 3). While the volume of irrigation needed to initiate leaching appears to be directly affected by substrate moisture deficit (in larger containers, with low sprinkler:substrate surface ratio), the volume of irrigation required to cease leaching appears to be consistent once the substrate is saturated. With the substrate used in this study, this volume was about 10% of container capacity, and fluctuated slightly for the 0% target (Figure 8), which probably did not saturate the substrate. Leaching based on container capacity can be used to accurately control final leaching volumes. With the tipping bucket sensors incorporated into the irrigation system, leaching recommendations based on a targeted percent of container capacity would be much easier to follow, provided the minimum desired leaching volume is around 10% of container capacity. Additionally, since actual values were a consistent amount greater than the target, despite size and moisture deficit, desired target leaching volumes can be better attained by applying predicted excess. In theory, zero leaching could be attained. Further research is needed to determine this relationship for additional substrates and container sizes, as well as correlation of water volumes and irrigation frequencies needed to allow proper plant growth and development.

The gradual decrease in salt concentration of the effluent aliquots may be due to salt accumulation in the upper substrate profile, from the tendency of solutes to move vertically with high evaporative conditions. Slight increases in salt concentration towards the end of leaching may be due to the fact that water following the shortest, least tortuous paths through the substrate

exit the container first, with less contact with substrate solutes. Water following a more tortuous path exits the container later and has more time to dissolve substrate solutes. Kerr and Hanan (1985) leached mixtures of peat moss, perlite, and glass beads in saturated-flow columns. Multiple container capacities of a low-EC solution were passed through the columns. While none of their mixtures contained pine bark, as in this study, one mixture with a similar bulk density showed a decrease in salt concentration of about 1 mS/cm-1 (1000mmhos/cm^{-1}) after one container capacity of effluent had passed. Several containers in this experiment decreased more than 1 mS/cm^{-1} after less than one container capacity leached (Figures 9b, e, f, g, h, i). While most of Kerr and Hanan's concentration curves became steady at 0.05 mS/cm^{-1}, the concentration curves from this experiment reached minimum values of 1.5-3.0 mS/cm^{-1}. It is not known if further leaching would have increased salt removal in this experiment; however, since it is possible that slow moving water is responsible for the slight increase in concentration at the end of the curves, it is possible that further leaching at a slower rate could remove more solutes. Hanan et al., (1981) proposed this idea in a study evaluating the salt-removal efficiency of several substrates with differing physical properties. He found that substrates with porosities of 70% and above had very high percolation rates and very low efficiency of salt removal. He also found that as effluent salt concentration decreased, the rate of salt removal decreased as well. The substrate in our study had an average porosity of 71%, so water moving through the profile may have been flowing in a very limited path, with unequal wetting and therefore salt leaching of the total mass of substrate. Additional research would determine the irrigation volumes and frequency needed to adequately lower EC. The proposed PCC method would allow for accurate control and accounting for irrigation and leaching volumes in such a study.

Conclusion

The findings of this study indicate that a predictable relationship between target leaching fraction and actual leaching fraction is not possible without accounting for container size and moisture deficit. Furthermore, results showed that leaching fractions do not represent consistent leaching volumes and can therefore be misleading when using to control leaching volumes. A much more predictable relationship exists between target and actual percent of container capacities leached, that improves volume prediction by 814%. Therefore, it is recommended that, with tipping bucket sensors, irrigation should be shut off according to the proportion of container capacity leached, not the proportion of irrigation applied that has leached. The consistent amounts leached, despite container size, moisture deficit, and target, allow growers to decide how much they would like to leach. It is not known if the 10% excess leaching beyond target would occur with additional substrate types and container sizes, but it is predicted that, nevertheless, a consistent excess amount would be seen. Further substrates and container sizes should be examined to determine the robustness of the suggested model.

Moisture deficits did not affect the biological relationship between target and actual percent of container capacities leached, nor did they affect the rate of salt concentration decrease in effluent. However, in larger containers, higher moisture deficits decreased the volume of water applied at the initiation of leaching, indicating inefficient substrate wetting. This supports previous research claiming the difficulty of rewetting dried-out nursery substrate. Therefore, it is recommended growers do not allow their substrates to attain moisture deficits in excess of 0.30 from container capacity, because the path of percolating water and water-absorbance efficiency may change to limit the effectiveness of leaching. Once saturated, however, leaching appears to continue for a consistent water volume despite initial differences in moisture deficit.

CHAPTER 3

USING TARGET AND ACTUAL PERCENT CONTAINER CAPACITIES TO LEACH CONTAINER NURSERY CROPS

Introduction

Recent attention has focused on reducing leaching from nursery containers, which wastes both water and fertilizer if done excessively. Better tools and protocols are needed to help growers control irrigation and leaching. Measuring container effluent volumes using tipping bucket sensors is a simple and effective way to control irrigation and leaching. In substrate-filled containers, when total effluent volume is related to the effluent volume passed at irrigation termination, based on the container capacity, a predictable relationship exists that can allow growers to target a specified volume of effluent (Chapter 2). This relationship predicts the actual percent of container capacity leached (APCC) for a given target percent of container capacity (TPCC), and has been found to be constant for a given substrate in a given container size, and may therefore be useful with indicator plants if the relationship holds constant throughout the growing season of a given crop. The previous study was limited to a single set of physical and/or chemical characteristics for the substrate on which it was performed, and did not include interferences from plant roots. In reality, substrates in containers change over time, as plant roots fill the air spaces and substrate particles settle, segregate, and decompose. These processes may have effects on the water retention properties and hydraulic conductivities of the container profile, and can therefore have an effect on the relationship between APCC and TPCC. The extent and speed with which water passes through the profile depends on the pore arrangement of the substrate, which depends on the particle size distribution and degree of settling, compaction, and root presence. Generally, settling and compaction reduce the total porosity of the substrate, while increasing root growth decreases the air-filled porosity of the substrate

(Allaire-Leung, Caron, and Parent, 1999; Cannavo et al., 2011; Jackson, Wright, and Seiler, 2009). The result is fewer large pores and more small pores that retain water, thus increasing container capacity. Several studies support the assumption that increases in root growth increase the container capacity of substrate-filled containers (Allaire-Leung et al., 1999; Altland, Owen, and Gabriel, 2011; Cannavo et al., 2011; Jackson et al., 2009). Therefore, the objectives of this experiment were to determine how particle size distribution and root mass changed over time, and how these changes affected the container capacity of the substrate and the relationship between TPCC and APCC.

Materials and Methods

Preparation of Substrate

Substrate was composed of pinebark screened to <15.9mm, amended with 0.59 kg N m^{-3}, 0.30 kg P m^{-3}, and 0.3 kg K m^{-3} (Sta-Green Corporation, St. Louis, MO). Three known masses of moist substrate were oven-dried to determine percent dry-matter of substrate (Eq. 1).

$$\%DW_1 = \frac{Mass_{oven-dry}}{Mass_{moist}} \quad \text{(Eq. 1)}$$

A 100g sample of oven-dry substrate was passed through a series of 12 standard sieves (12.5, 9.5, 6.35, 3.35, 2.36, 2, 1.4, 1, 0.5, 0.25, 0.11, 0.05mm, and pan) and shaken for 3 minutes at 278 oscillations/minute in a Ro-Tap® shaker (W.S. Tyler Industrial Group, Mentor, OH). Contents from each sieve were weighed to determine particle size distribution.

Potting

Taxodium distichum liners (3.8L) were removed from their containers and substrate scraped from the root ball until visible roots showed. Three known masses of liner substrate were oven-dried to determine percent dry matter (Eq. 2).

$$\%DW_2 = \frac{Mass_{oven-dry}}{Mass_{moist}} \quad \text{(Eq. 2)}$$

Three trees were weighed and averaged to determine initial fresh weight (M_{iFW}). These trees were uniformly potted into plastic-lined 10.4L containers and weighed again and averaged to determine total potted weight (M_{TPW}). Mass of added substrate (M_{AM}) was determined by subtracting the initial fresh weight from the total potted weight (Eq. 3).

$$M_{AM} = M_{TPW} - M_{iFW} \quad \text{(Eq. 3)}$$

Potted trees were saturated. After two hours, each container was weighed before the plastic was punctured to allow gravitational drainage of excess water. After one hour or no visible water exiting the containers, containers were re-weighed. Based on saturated (M_s) and drained masses (M_d), pore space (f) was determined (Eq. 4):

Air-filled porosity: $$f_a = \frac{(M_s - M_d) \times \rho_w}{V_t} \quad \text{(Eq. 4)}$$

where M_s is the saturated mass of the substrate, M_d is the drained mass of the substrate, ρ_w is the density of water, and V_t is the total volume of fill.

Trees were removed from containers and shaken vigorously until no substrate clung to the roots, and weighed again (M_{FW}). This weight was subtracted from the initial fresh weight of the tree to determine mass of initial substrate around the liner's root ball (M_{iM}) (Eq. 5).

$$M_{iM} = M_{iFW} - M_{FW} \quad \text{(Eq. 5)}$$

The total dry matter per container was determined by equation 6:

$$M_{OD} = (\%DW_1 \times M_{AM}) + (\%DW_2 \times M_{iM}) \quad \text{(Eq. 6)}$$

Initial container capacity (K) was determined by subtracting the tree fresh weight (M_{FW}) and container dry weight (M_{OD}) from the drained weight (M_d) (Eq. 7).

$$K = M_d - M_{FW} - M_{OD} \quad \text{(Eq. 7)}$$

Remaining trees were potted into 10.4L containers by adding the mass of substrate (M_{AM}) from equation 3 to each container and liner. The original dry matter (M_{OD}) calculated from equation 6 was assumed for remaining trees and used for the remainder of the experiment.

Crop Maintenance

Trees were maintained on a canyard and overhead irrigated at 0.66 mm min^{-1} for ten minutes, five times daily for the first six weeks. Thereafter, irrigation was reduced to 0.66 mm min^{-1} for fifteen minutes, three times daily. Trees were topdressed with a low rate of 12-6-6 controlled release fertilizer (Nursery Special, Sta-Green Corporation, St. Louis, MO) at five weeks after potting.

Calculation of Moisture Deficit

At the beginning of 1, 5, and 14 weeks (for first experiment) and 1, 8, and 17 weeks (for validation experiment) after potting (WAP), three trees from the crop were used to recalculate container capacity for the rest of the trees in the simulation. Trees were saturated by submerging their containers in water for 10 minutes and allowing to drain until no effluent was observed, then weighed. Trees were removed from the containers and shaken vigorously until no more substrate clung to the roots, and weighed to determine a new fresh weight (M_{FW}). New container capacity was calculated by using equation 7 and substituting the new drained weight and fresh weight. Trees for the simulation were removed from the canyard and placed in a greenhouse to attain moisture deficits of 0.05 or 0.20 from container capacity. Deficit was determined by weighing containers, subtracting the fresh weight and dry weight average of the three trees used in the container capacity recalculation, and dividing by the new container capacity (Eq. 8).

$$Deficit = \frac{M_{container} - M_{FW} - M_{OD}}{K} \quad \text{(Eq. 8)}$$

Leaching Apparatus

The leaching apparatus for simulations was the same as described in Chapter 1.

Leaching Simulations

Irrigation was applied at 2.19 mL s^{-1} via 360° spray stakes. Effluent volume data measured using tipping-bucket sensors were stored using a datalogger (CR23X, Campbell Scientific, Logan, UT) (See Chapter 1, Figure 2), and included the duration of each irrigation application, time to initiate leaching, and the effluent volume. The logger calculated volume of water applied by multiplying seconds elapsed by the application rate. Target percent container capacities (TPCCs) were calculated by dividing the volume of effluent by the container capacity (K) (Eq. 9).

$$TPCC = \frac{Volume_{leached_t}}{\mathrm{K}} \times 100 \qquad \text{(Eq. 9)}$$

Calculations were updated every five seconds and displayed on a computer screen. Containers were irrigated until the TPCC (0%, 10%, 30%, or 50%) was achieved. For the 0% treatment, irrigation was ended at the first drop of effluent. Effluent was measured until drainage ceased. Total volume leached was divided by container capacity (K) to determine actual percent container capacity (APCC) (Eq. 10).

$$APCC = \frac{Volume_{leached_f}}{\mathrm{K}} \times 100 \qquad \text{(Eq. 10)}$$

The initial 120mL of effluent was collected from each container, as well as a 120mL aliquot from the remaining effluent. Electrical conductivity was measured on these samples using a portable EC meter (HI 98312, Hanna Instruments, Smithfield, RI).

Harvest

After leaching simulations were performed, trees were removed from their containers and shaken vigorously and washed until no more substrate clung to the roots. Trunks were severed at

the root ball and root and shoot fresh weights were taken. Total tree fresh weights were recorded and subtracted from total container weight before simulation to determine actual moisture deficit, using equation 8. Root balls were dried in an oven at 65°C for 72 hours and weighed again.

Experimental Design

This simulation experiment included one species, one container size, two moisture deficits, four target percent container capacities (0%, 10%, 30%, or 50%), three harvest dates (WAP), and four replications per treatment for a total of 96 simulations, arranged in a 1x1x2x4x3x4 factorial design.

Statistical Methods

Linear regression models were fitted in SAS (Version 9.1, SAS Institute, Cary, NC) using the regression procedure for APCC with fixed model parameters of TPCC, moisture deficit, and weeks after potting (WAP).

Results

Substrate Physical Properties

Particle size distributions for the original liner substrate, added substrate, and substrate sampled from 17-week old planted containers are shown in table 6. No statistically significant differences were found in the proportions of coarse, medium, or fine particles between the beginning and end of the experiment, however, a slight increase in coarse and a slight decrease in fine particles were observed.

Initial physical properties for fallow (substrate-only) and planted containers are given in table 7. Air-filled porosity (f_a) increased 8%. Decreases were seen for container capacity (K), moisture deficit at container capacity ($\theta_{(K)}$), and bulk density (D_B).

Initial container capacity of fallow, substrate-filled 10.4L containers was 4171mL. Container capacities used to control irrigation at each simulation date are shown in table 8.

Table 6. Particle size distribution in original liner substrate and in 15.9mm-screened pine bark substrate in planted 10.4L containers at 0 and 17 WAP used for leaching simulation experiment in summer 2012.

U.S. standard sieve no.	Sieve opening (mm)	Percent composition (%)[a]		
		Original liner root ball[b]	15.9mm PB[c] 0 WAP	15.9mm PB 17 WAP
1/2	12.50	8.35	3.47	3.01
3/8	9.50	12.41	5.87	6.85
1/4	6.35	13.50	12.88	14.27
6	3.35	18.07	26.35	29.78
8	2.36	8.22	10.84	13.49
10	2.00	2.89	3.84	4.76
14	1.4	6.43	8.35	9.05
18	1.00	5.35	6.50	6.05
35	0.50	8.84	9.87	7.01
60	0.25	7.49	6.21	2.96
140	0.11	5.51	3.79	1.51
270	0.05	1.88	1.18	0.60
Pan	0.00	1.05	0.84	0.64
Texture[d]	Coarse	63.45	63.26 a[e]	72.17 a
	Medium	20.61	24.71 a	22.12 a
	Fine	15.94	12.03 a	5.71 a

[a]Values averaged from three oven-dried samples.
[b]Substrate scraped from liner rootball as received from wholesaler nursery.
[c]Added substrate composed of pine bark screened to ≤15.9mm with hammermill.
[d]Texture grouping: coarse > 2.0mm; medium > 0.5mm and <2.0mm; fine < 0.5mm
[e]Differences within rows between 0 WAP and 17 WAP determined using pooled t-test.

Table 7. Substrate physical properties (air-filled porosity (f_a), container capacity (K), moisture deficit at container capacity ($\theta_{(K)}$), and bulk density (D_B)) at 0 WAP in planted and fallow 10.4L containers.[a]

	f_a	K (mL)	$\theta_{(K)}$	D_B (g cm^{-3})
Substrate-only	0.29	4171	0.40	0.22
Planted	0.37	3226	0.31	0.19

[a]Averaged over three replications.

Container capacities did not significantly increase at every simulation. Experiment 1 container capacities showed a decrease with the addition of a plant (22.7%). Container capacities increased significantly from weeks 0 to 1, and from weeks 1 to 5, with a 16% and 9.74% increase,

Table 8. Container capacities from three sampled fallow or planted containers at each simulation date in leaching simulation experiment during summer 2012.[z]

Experiment 1		Experiment 2	
WAP[y]	Container Capacity (mL)[x]	WAP	Container Capacity (mL)[x]
0 fallow[w]	4171 a[v]	.	.
0 planted	3226 b	.	.
1	3742 c	1	4307 a
5	4106 a	8	4069 b
14	4178 a	17	4111 ab

[z]Values averaged from three planted containers
[y]WAP = Weeks After Planting
[x]Container capacity is the amount of water held in the planted container after drainage ceased.
[w]Measured on fallow containers at potting, 0 WAP
[v]Means separated within columns using Tukey's Studentized Range Test ($p \leq 0.05$; n=2).

respectively. A 1.77% increase in container capacity occurred from weeks 5 to 14, and was not significant. A total increase of 29.5% occurred from week 0 to week 14, with the final container capacity not significantly different from that of fallow containers at 0 WAP. Experiment 2 container capacities showed significant change between weeks 1 and 8 only, with a 5.53% decrease in container capacity. A 1.03% increase in container capacity occurred from week 8 to week 17, and was not significant. In total, a decrease of 4.5% in container capacity occurred from week 1 to week 17. In both experiments, container capacity did not correlate with increases in total plant weight of trees sampled for container capacity determination, and these tree weights only increased significantly from weeks 5 to 14 in experiment 1, and from 1 to 8 weeks in experiment 2. Correlation between container capacity and weeks after planting existed only in the first experiment (0.77057, $p \leq 0.05$).

An increase in time to initiate leaching was found only between 8 and 17 WAP in experiment 2, and were found to have correlations with WAP (0.42457, $p \leq 0.05$) and dry root weight (0.20313, $p \leq 0.05$). No other differences in time to initiate leaching were noted.

Mean fresh and dry root masses for each simulation date are shown in table 9. In experiment 1, fresh and dry root weights increased at every simulation date, and significantly from 5 to 14 weeks. By week 14, fresh and dry weights had increased 60.2% and 57.4%, respectively, from week 1. In experiment 2, dry root weight decreased from week 1 to week 8

Table 9. Mean root mass of all trees used in each simulation in leaching experiment conducted in summer 2012.

Experiment 1			Experiment 2		
WAP[z]	Fresh mass (g)	Dried mass (g)	WAP	Fresh mass (g)	Dried mass (g)
1	189.8 a[y]	58.1 a	1	242.1 a	77.3 a
5	238.7 a	64.2 a	8	317.5 b	69.3 a
14	353.0 b	97.5 b	17	366.8 c	97.5 b

[z]WAP = Weeks After Planting
[y]Means separated within columns using Tukey's Studentized Range Test ($p \leq 0.05$; n=2).

by 10.4%, and increased by 36.5% by week 17. Fresh root weight, however, increased significantly at each simulation week, 31.1% and 20.4% by weeks 8 and 17, respectively (Figure 10).Calculation of moisture deficit at each simulation using the container capacity of the three harvested trees were not exactly attained, the cause being the differences in tree mass.

Linear Regressions

Linear regressions for APCC vs. TPCC showed no differences across moisture deficit and WAP in both experiments (Figures 11-13). Regressions were similar to those found in the previous study (Chapter 1), but less effect was found with increasing moisture deficit. Also, as in

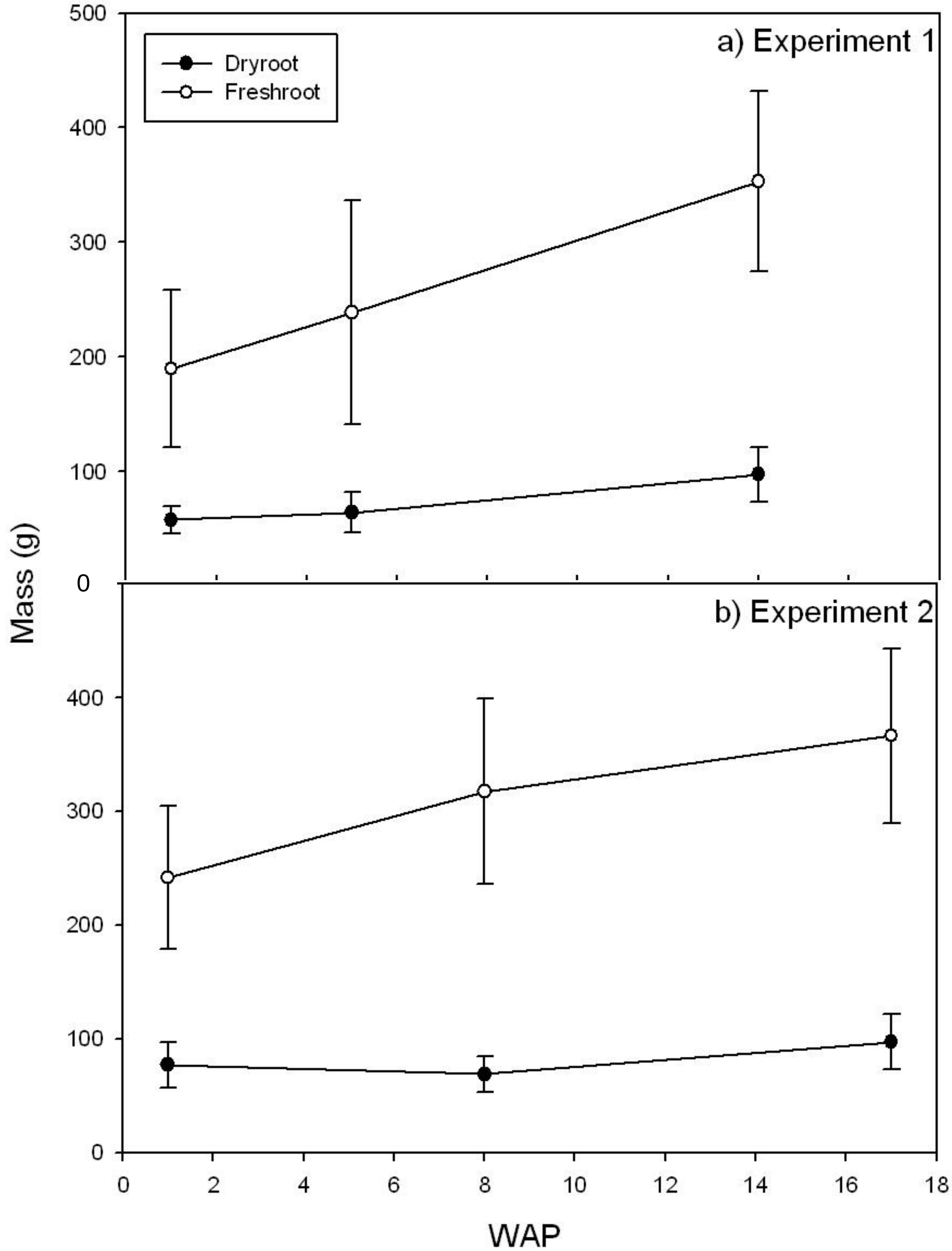

Figure 10. Average masses of fresh tree roots immediately after each simulation and after drying for 72 hours at 65°C in experiment 1 (a) and experiment 2 (b).

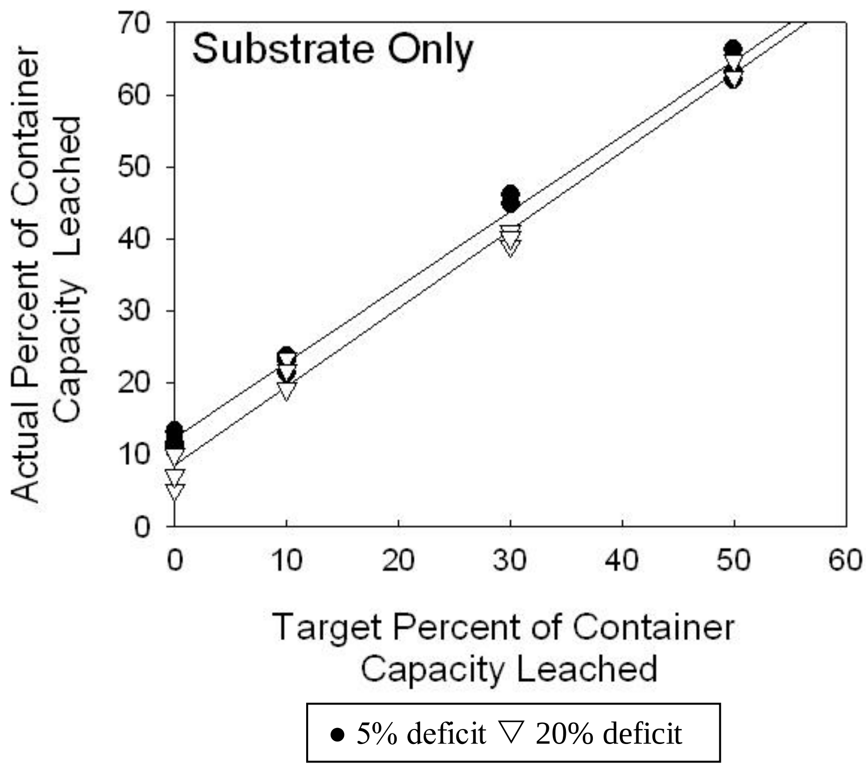

Figure 11. Actual percent of container capacity leached after ending irrigation at specified target percent of container capacity leached in fallow, substrate-filled containers, at two deficits (5% and 20% from container capacity).

Chapter 1, APCC were consistently around 10% greater than TPCC. Regressions were not altered despite significant changes in container capacity and rooting. The y-intercepts and slopes of regressions by WAP did not appear to change with significant changes in container capacity (Figure 14). When APCC was regressed to TPCC disregarding deficit and WAP, a mean square error of less than 0.001, and R^2 values of over 98% were found in each study (Figure 15).

Electrical conductivity measured on initial and final aliquots did not change significantly, and were nearly all below 0.6 by the second simulation date (data not shown).

Discussion

Similar to Chapter 1 results, APCC leached were consistently around 10% greater than TPCC, further supporting that leaching based on container capacity with tipping bucket sensors can be predictable for a given set of physical properties. When APCC was regressed to TPCC,

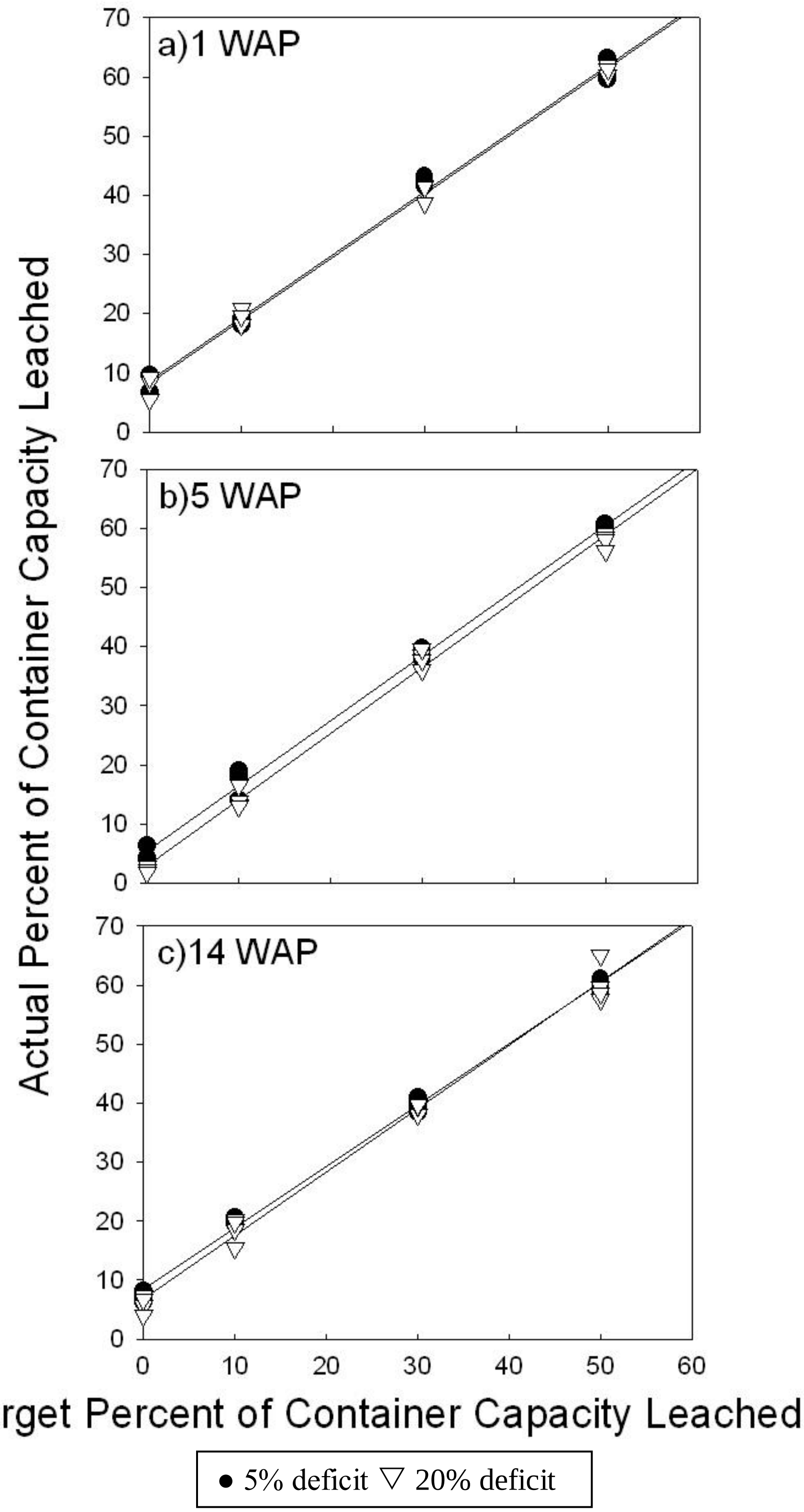

Figure 12. Actual percent of container capacity leached after ending irrigation at a specified target percent of container capacity leached in experiment 1 after (a) 1 WAP, (b) 5 WAP, and (c) 14 WAP in planted containers, at two deficits (5% and 20% from container capacity). WAP = Weeks After Potting.

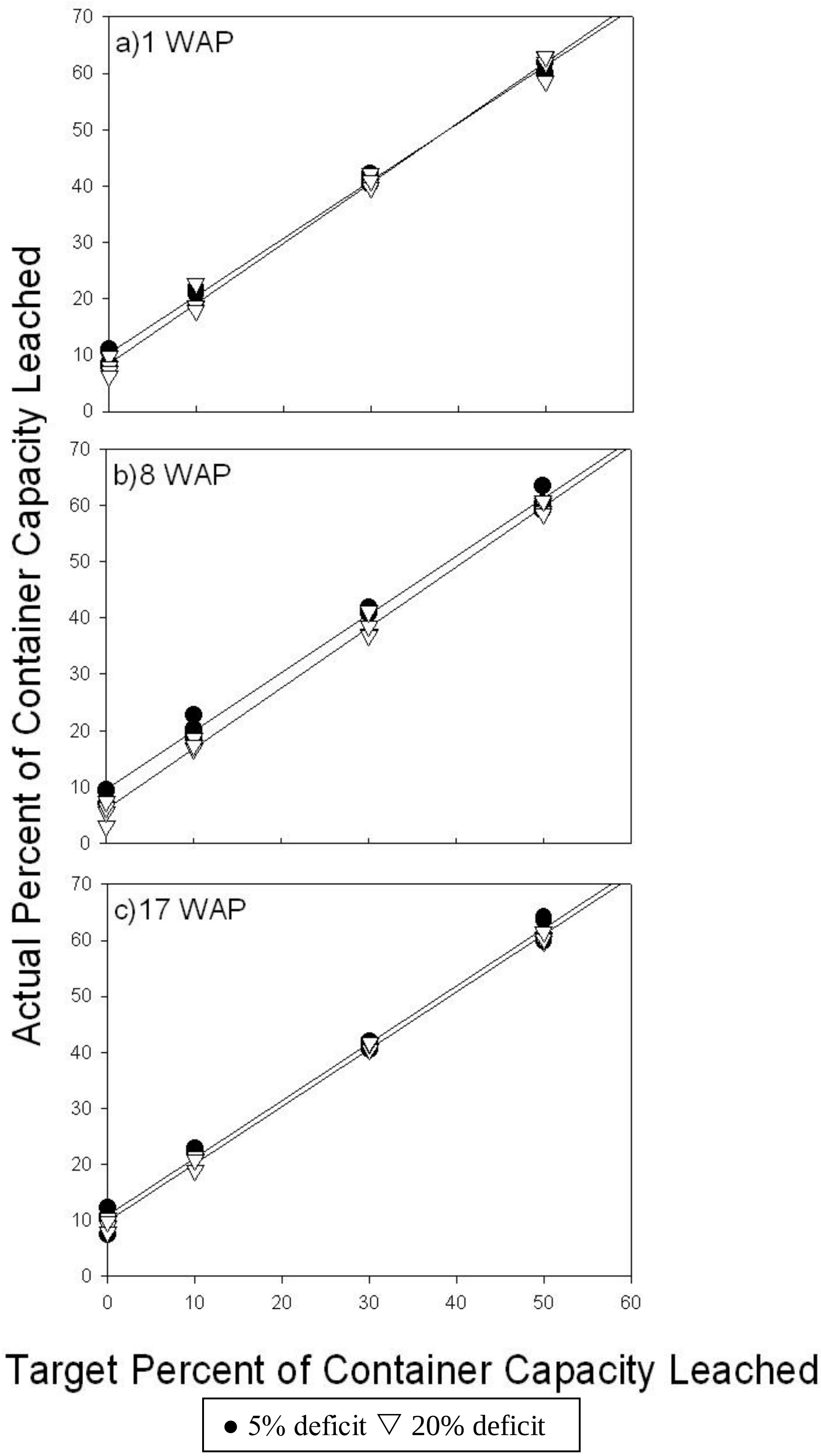

Figure 13. Actual percent of container capacity leached after ending irrigation at a specified target percent of container capacity leached in experiment 2 after (a) 1 WAP, (b) 8 WAP, and (c) 17 WAP in planted containers, at two deficits (5% and 20% from container capacity). WAP = Weeks After Potting.

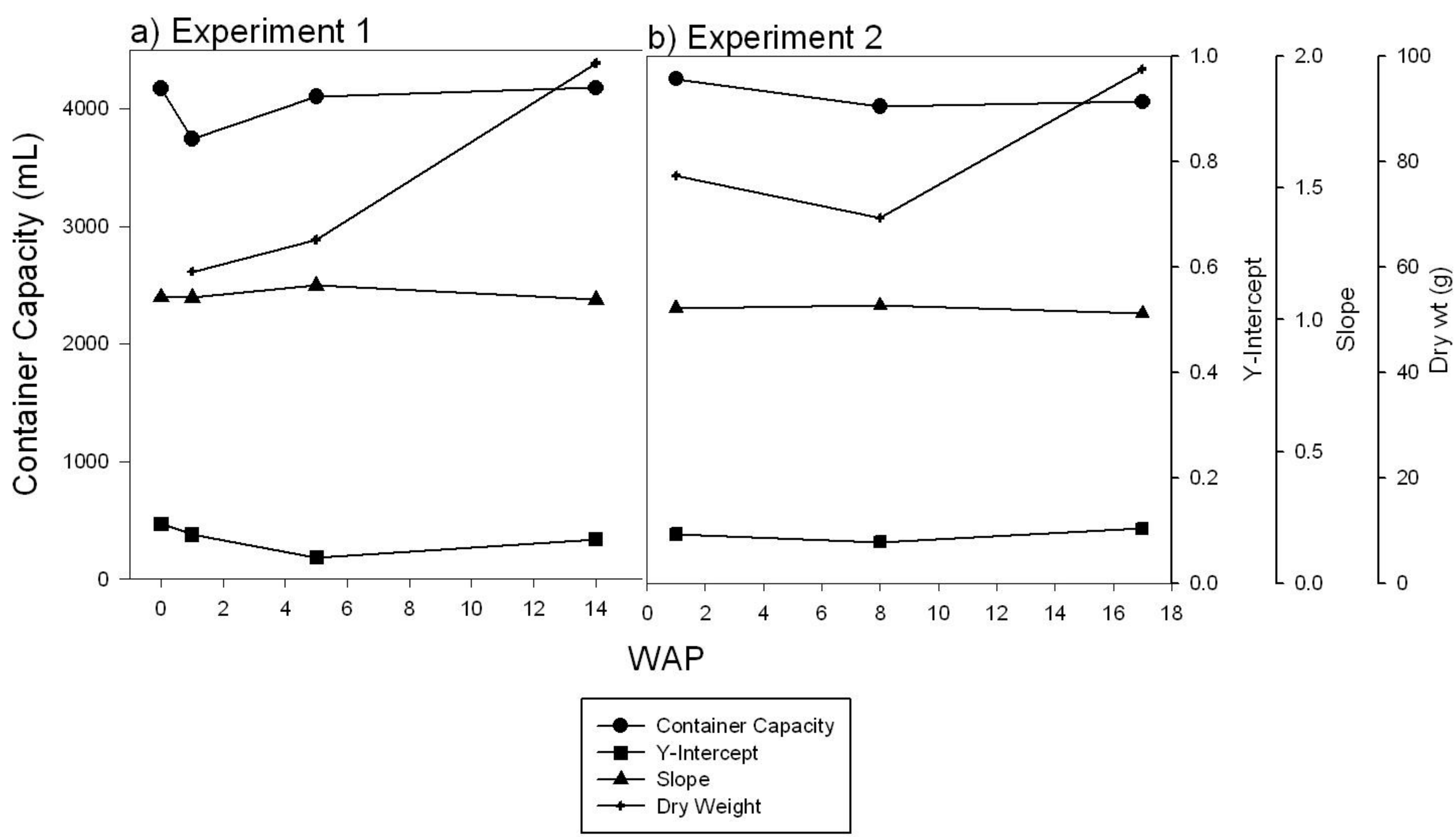

Figure 14. Interaction of container capacity and dry root weights on the Y-intercepts and slopes of regressions for individual WAP (deficits combined) in experiments 1 (a) and 2 (b).

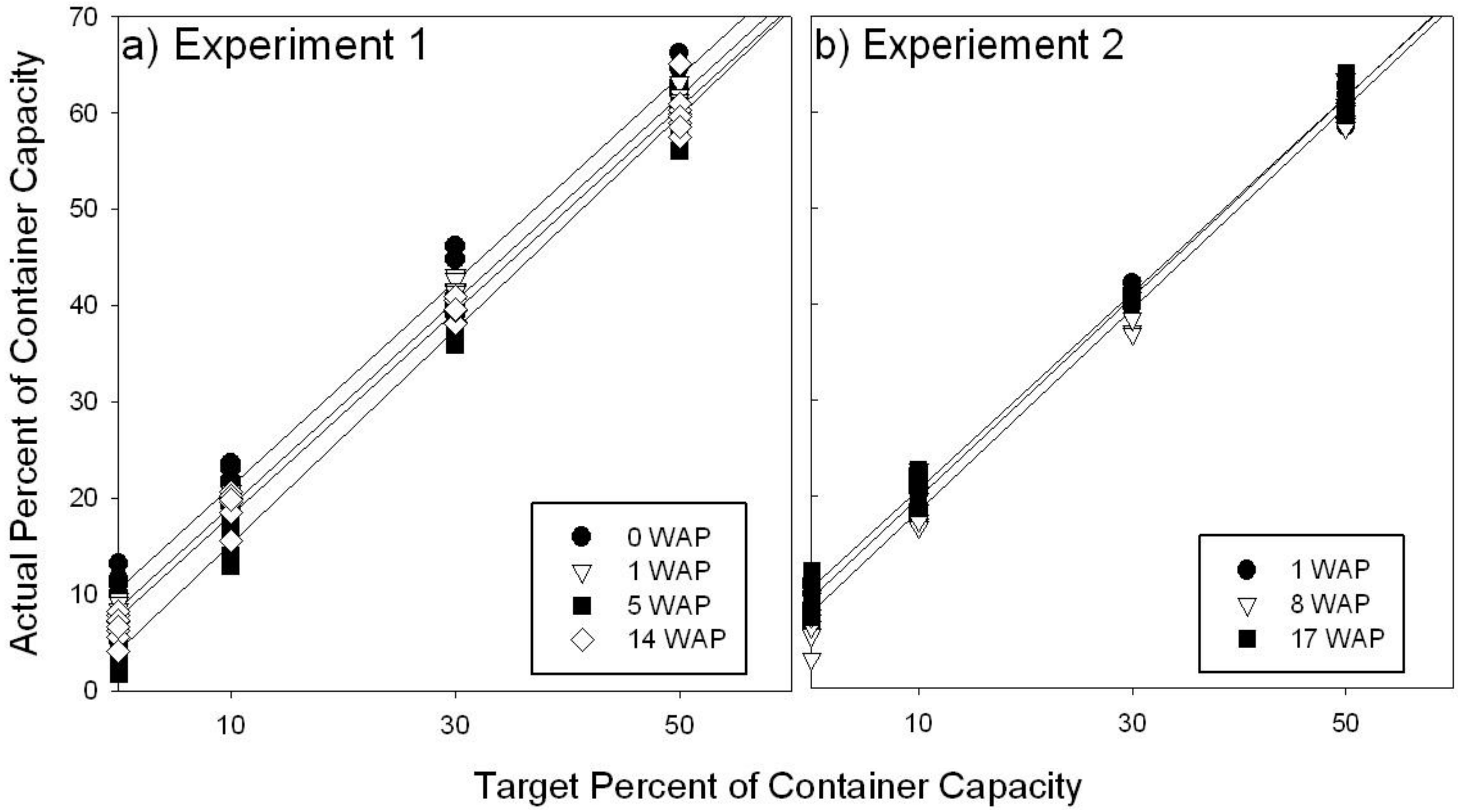

Figure 15. Actual percent of container capacity leached per target percent of container capacity leached for experiments 1 and 2. Data in each graph include both moisture deficits and all WAP treatments.

disregarding effects of deficit and WAP, a mean square error of less than 0.001, and R^2 values of over 98% were found in each study (Figure 15). Furthermore, regressions did not change despite significant changes in container capacity and rooting. Significant changes in container capacity did not appear to modify the y-intercepts and slopes of regressions by WAP (Figure 14). The accuracy of the PCC method was not reduced by adding plants, as the MSE of these studies were even lower than in Chapter 1 results on substrate-only pots, further indicating that leaching based on container capacity is highly accurate and predictable.

Physical properties of container profiles were not consistent with previous findings that generally found decreases in air space and increases in container capacity with the addition of roots over time (Altland et al., 2011; Jackson et al., 2009). The addition of plant roots in this study had the opposite effect at 0 WAP (Table 7) in this study and are likely due to the fact that, immediately after potting, substrate did not settle around the existing root structure, leaving air spaces and pores too large to hold water. Container capacity changes over time were consistent with previous research in the first experiment. In a study on slightly larger containers (15L), Jackson et al. (2009) found an 11.4% increase in container capacity between fallow, substrate-filled containers and containers at 70 weeks post-planting. Altland, et al. (2011) also witnessed slight increases in container capacity with the presence of plants in containers compared to substrate-only containers exposed to production conditions. In this experiment, while final container capacity was not greater than in the initial, fallow containers, increases were seen in planted containers for the remainder of the experiment (29.5% total increase) (Table 8). Increases in rooting were seen over the course of both experiments, but correlation between root mass increase and container capacity could not be analyzed, as container capacity measurements were not taken on containers that were simulated and had roots harvested. Cannavo et al. (2011) and Allaire-Leung et al. (1999) noted increases in container capacity with increased rooting, and

suggested the roots decreased the macroporosity and air space of the substrate, and an increase in smaller pores that hold water more easily. Although data were sampled from different containers, changes in container capacity were earlier in both experiments, whereas increases in root mass were later in both experiments. This suggests that the effects on container capacity were mostly due to settling or segregation of particles rather than changes in root penetration.

Although significant changes in particle size distribution did not occur after 17 weeks, the slight changes in textures classes are attributed to larger particles breaking down, slightly increasing proportions of medium particles, and finer particles flushing from the container with irrigation water.

Cannavo et al. (2011) also noted decreases in the hydraulic conductivity over time, and suggested the cause as increasing root growth. No increases in time taken to start leaching occurred in experiment 1, however, increases were noted in experiment 2, and were found to have weak correlations with WAP and dry root weight. Perhaps most root growth on these crops were fibrous roots, which would have either been lost in the harvest process or added insignificant weight to overall root mass, but may still have affected the pore structure of the substrate. However, settling and segregation of particles over time is more likely the cause of such pore reorganization.

The extremely low salt concentrations are probably due to CRFs dissolving too quickly to give significant EC measurements at any point in the experiment, even after topdress. This issue would need to be further addressed in future research. The change in electrical conductivity during the leaching process in the presence of roots and over the season would be valuable information when using this system.

Conclusion

In this study, time did not greatly affect the particle size distribution and rooting mass, however, significant changes were measured. Further research should include a longer growing season so the effects of time on substrate and rooting can be adequately assessed. Changes in container capacity were only noted in the first experiment, and only minor changes in resulting actual volumes leached were noted. The relationship between actual and target percent of container capacities leach proved robust despite minor changes in container capacity and rooting. Greater changes will still need to be assessed; however, the findings of this study show that introduction of plants did not decrease the accuracy of the PCC leaching method. This further indicates that leaching nursery containers based on container capacity with tipping bucket sensors provides an accurate way to control leaching volumes. Further research is still needed to determine what volumes are needed to reduce substrate electrical conductivities to desired levels. Such research would be greatly assisted using the system presented here, which provides a more accurate way to assess leaching volumes than when using leaching fraction.

CHAPTER 4

OVERALL CONCLUSIONS

Overuse of water and excess nutrient runoff in container nurseries pose a consumptive and environmental threat, and occur due to lack of knowledge and simple ways to monitor irrigation application. In addition, overirrigation and excessive nutrient runoff are a waste of money to the grower. Reducing leaching volumes is one way to reduce this wastage, and can be easily done with tipping bucket rain gauges. In order to encourage wider implementation of effluent monitoring, better guidelines need to be given on how to do so.

Chapter 1 results showed that tipping bucket sensors could be easily used to monitor effluent from nursery containers. The system in which they were used could be incorporated into a commercial operation by setting up a few “indicator plants” per crop, which would relay effluent data to the system controlling irrigation to the remainder of the crop. Further, it was shown that using leaching fraction to control irrigation resulted in varied effluent volumes, depending on the container size and initial moisture content. Leaching based on container capacity showed increased predictability and accuracy (by 814%), with consistent final effluent volumes leached despite differences in container size and moisture deficit. Results also supported the difficulty of rewetting dried-out substrates, suggesting that in drier container profiles, water is absorbed less efficiently, therefore reducing the water’s ability to leach salts. It is therefore recommended that growers not allow their substrates to dry beyond 30% of container capacity, as leaching may occur prematurely, before the mass of the substrate is wetted. In this case, it will take longer to saturate the substrate, allowing more leaching to occur that does not necessarily remove more salts. Finally, results showed that despite differences in initial moisture content, once saturated, containers usually leached no more than 10% of container capacity more

after the end of irrigation. This suggests for other mixes of differing physical properties, the total leaching volume can still be predicted based on the initial post-irrigation effluent.

Chapter 2 results showed that minor changes in container capacity and rooting did not reduce the accuracy of leaching based on container capacity. Perhaps larger changes would affect its predictability; in that case, container capacity could be easily measured at various times during crop production and the new container capacity incorporated into the calculations. This is not expected to be very complicating to system, comparatively, as changes in rooting and container capacity would likely affect leaching fraction as well. Separate studies need to be done on how container capacity and rooting change over time.

Research on volumes needed to reduce the electrical conductivity within substrate profiles still needs to be done, but it is worth noting that most containers in the first study had reductions in effluent electrical conductivity after less than one container capacity leached.

Current leaching fraction recommendations are confusing, require accounting of multiple parameters, and result in arbitrary effluent volumes. The studies discussed here have shown, despite the time lag occurring between the time when irrigation is shut off and the time when leaching stops, controlling irrigation based on the percent of container capacity leached with tipping bucket sensors offers a simple, comparatively affordable and highly accurate method of reducing container leaching and controlling irrigation volumes, therefore reducing nursery runoff.

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VITA

Maureen Estelle Thiessen was born as the second child of Myron and Elinelle Thiessen. Born in San Jose, California, and raised in Baton Rouge, Louisiana, she graduated from Baton Rouge Magnet High School in the spring of 2006, and enrolled at Louisiana State University that fall. She completed her Bachelor of Science degree in Biological Sciences in 2010, and afterward worked a three-month internship for the Monsanto Company in Woodland, California. She returned to Louisiana State University in the fall of 2010 and enrolled in a graduate program in the department of horticulture, under the direction of Dr. Edward Bush. Maureen is a candidate for a Master of Science degree in horticulture with a research emphasis on water use efficiency in container nursery crops.