Water and nutrient transport dynamics during the irrigation of containerized nursery crops

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Abstract

Increased water- and fertilizer-use-efficiency in containerized crop production, via reduced water loss, enhances crop-available nutrients while reducing non-point source agrichemical contributions in accordance with regulatory standards. Previous studies detailed nutrient leaching patterns throughout crop production seasons, leaving little known about water and dissolved nutrient (solute) movement through soilless substrates during irrigation. The following experiments evaluated fundamental water and solute transport principles through pine-bark based substrates. 1) *Ilex crenata* Thunb. 'Bennett's Compactum' were grown in 2.7 L containers. Tensiometers detected wetting front (WF) movement throughout the substrate during irrigation. 2) Tracer solution (containing NO_3^-, PO_4^{3-} and K^+) and deionized water (DI) were applied to substrate-filled columns to characterize tracer breakthrough under saturated and unsaturated conditions. 3) Controlled-release fertilizer (CRF) was topdressed (surface-applied), incorporated (throughout substrate), dibbled (center of substrate) or not applied to fallow substrate, irrigated with DI and leachate analyzed to determine nutrient concentrations throughout irrigation. Tensiometers revealed that seasonal root growth affected substrate pre-irrigation moisture distribution. Wetting fronts channeled through the substrate before becoming thoroughly wetted. Tracer breakthrough occurred with less effluent volume under unsaturated conditions. Breakthrough of NO_3^- and PO_4^{3-} was relatively conservative, though 37% of K^+ was retained by the substrate. Leachate concentrations for topdressed and incorporated CRF peaked early (first 50mL effluent) before diminishing with continued leaching. Leachate concentrations for dibbled CRF initially increased (first 150mL leachate), plateaued and then diminished. These results show the relative rapidity which water and solutes move through pine-bark during irrigation and demonstrate methods for future research on within-irrigation solute transport.

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Table of Contents

List of Tables

List of Figures

Chapter 1

General Introduction and Review of Literature

Problem statement

According to the USDA (2010), $3.8 billion of nursery stock was sold in the U.S. in 2009, of which $2.5 billion (66%) was containerized plants. Traditionally, soilless substrates in containerized plant production are of relatively low water holding capacity (compared to mineral soils) and require frequent irrigation to continually supply the crop with an adequate amount of water. However, the frequency which irrigation must be applied, often leads to the undesired leaching of mineral nutrients that reside in the substrate pore solution. Leached mineral nutrients are no longer available for crop growth and have the potential to be transported offsite. The leaching of applied mineral nutrients is a source of inefficiency that, if improved, may be an opportunity for growers to improve profitability. A reduction in the quantity of leached mineral nutrients may lead to improved crop growth and reduced fertilizer costs, as more nutrients would remain available to the crop and the need for supplemental fertilizer applications would be reduced. Furthermore, the aforementioned improvements in nutrient use efficiency may help the producers of containerized ornamental crops to comply with current or future regulatory standards regarding non-point source agrichemical contributions to local watersheds, such as the total maximum daily load (TMDL) limits for agrichemical contributions discussed by Majsztrik and Lea-Cox (2013) in relation to the Chesapeake Bay watershed.

Progressive researchers, extension agents and growers believe that they will need to improve the efficiency with which water and mineral nutrients resources are used to ensure they remain profitable, and stay ahead of potential environmental regulation. However, the current body of literature lacks insight into how solutes (i.e., mineral nutrients dissolved in water) are transported within and through a substrate during and immediately following water application (i.e., irrigation or rainfall). An understanding of these phenomena may allow for the refinement of crop production practices that lead to improved resource use efficiency

Current recommendations for reduced nutrient leaching

Horticultural researchers have collaborated to publish a set of best management practices (BMPs) (Bilderback et al., 2013) that producers of containerized ornamental crops may utilize to use to improve water- and nutrient-use efficiency. These BMPs largely involve recommended methods for crop nutrient and water management. The industry has responded positively, as indicated by generally favorable BMP adoption rates in regional and national surveys of major nursery crop production regions in the U.S. (Garber et al., 2002; Mangiafico et al., 2010; Schoene et al., 2006). For example, a national survey on green industry sustainability reported that 64.0% of growers were composting plant waste, 66.4% were using controlled-release fertilizer (CRF) and 69.6% were recycling plastic pots (Dennis et al., 2010).

Nutrient monitoring. Regular monitoring practices are vital to making informed decisions regarding crop nutrient management. It is recommended that growers monitor substrate nutrient status at least monthly, but preferably every two weeks during the growing season (Bilderback et al., 2013) to ensure that appropriate amounts of mineral nutrients are available to support ample crop growth. Many techniques exist to measure available nutrients such as vacuum extraction (Holcomb et al., 1982), pour-through extraction (Wright, 1986), saturated media extract (Warnecke, 1986) and in-situ sensors (Scoggins and Van Iersel, 2006). Each of these methods has advantages and disadvantages. The saturated media extract is a destructive method that requires removing a portion of the substrate for analysis. The pour-through extraction procedure involves applying water to the soil surface and displacing the soil solution, which can then be collected and measured. In-situ sensors involve a more significant up-front investment but provide an abundant amount of information. However, these sensors provide bulk electrical conductivity (EC) measurements (substrate, air and solution) rather than just the pore-water EC. Therefore, in-situ measurements pose a limitation because the air and substrate have inherently low EC and therefore the bulk reading may be lower than the true EC of the solution (Scoggins and Van Iersel, 2006).

Irrigation management and moisture monitoring. Decisions on when and with how much water to irrigate are important factors in managing the leaching of applied mineral nutrients. Techniques for determining the need to irrigate are largely based on an assessment of the substrate moisture content. This may include more advanced technologies, such as in-situ moisture sensors (Bayer et al., 2013) and gravimetric measurements (i.e., changes in container weight in relation to water application or evapotranspiration) (Prehn et al., 2010), or may simply involve routine monitoring by a trained irrigator.

Evaluating whether the proper volume of water was applied to the crop may be accomplished through the collection of leaching fractions (LF = volume of water leached / volume of water applied). With this measurement, a grower can adjust the volume of water applied to achieve the desired amount of leaching. Current BMP guidelines (Bilderback et al., 2013) recommend that the volume of water leached not exceed 15% of the volume applied. Maintaining low LFs, or reducing the volume of water leached during irrigation, through the management of water application volumes, is effective in reducing the total nutrients leached (Owen et al., 2008; Tyler et al., 1996).

Controlled-release fertilizer. Controlled-release fertilizers (CRFs) are a recommended mineral nutrient delivery method, whose use has been shown to be effective in reducing the nutrient content of water that leaches from nursery containers (Catanzaro et al., 1998; Wilson and Albano, 2011). A CRF contains encapsulated (plastic polymer coating), mineral nutrients that, in the presence of water, slowly dissolve and release to the surrounding substrate solution over an extended period of time, typically measured in months. This nutrient delivery method is widely adopted, as indicated by a nationwide survey where 66.4% of respondents in the green industry reported that they were currently using CRF (Dennis et al., 2010).

Common methods to apply CRF include incorporation (prills are distributed throughout the substrate), dibble (prills are placed in the center of the container substrate) and topdressed (applied to the surface). Release of nutrients from CRF is affected by application method. For example, Alam et al. (2009) reported that the maximum nutrient release rate occurs later in the season when CRF is topdressed than when incorporated. Furthermore, CRF placement method may lead to a non-uniform nutrient distribution throughout a substrate profile, as indicated by research that evaluated the effect of fertilizer placement on crop quality and weed growth in containers (Altland et al., 2004; Broschat and Moore 2003). A species-specific response in crop growth to the placement of CRFs and a decrease in weed growth were found when CRF was dibbled. As a whole, these studies suggest that nutrient availability and distribution is variable throughout a substrate profile and is affected by CRF placement.

Controlled-release fertilizers have been shown to exhibit a seasonal variability in their nutrient release rate, where CRFs release nutrients at a higher rate in the early portion of their life (Merhaut et al., 2006). Furthermore, release of mineral nutrients from CRFs into the substrate solution is cited to be a function of coating technology and temperature (Adams et al., 2013; Husby et al., 2003), where temperature fluctuations alter the coating’s porosity, either facilitating or limiting nutrient diffusion through the coating. Therefore, temperature is often utilized as a predictor of the quantity of nutrients that are released, with a given coating technology, into the substrate solution. Nutrients in the substrate solution that were not absorbed by the plant or bound to the substrate between irrigation events have the potential to be displaced and leach from a container at the next irrigation event. Therefore, the belief of the author that the total load of mineral nutrients that are leached during irrigation is a function the quantity of pre-irrigation, leachable nutrients in the substrate solution, the physical (i.e., porosity, moisture content at time of irrigation) and chemical properties (i.e., ion exchange capacity, ions bound to exchange) of the substrate. These factors likely affect the movement of water through the substrate and subsequently the transport of solutes in said water.

Considerable effort has been put forth to understand the release and leaching of mineral nutrients from containerized crop production systems, throughout a crop production season, where CRFs are used as the nutrient delivery method (Alam et al., 2009; Broschat and Moore, 2007; Cabrera, 1997, Colangelo and Brand, 2001; Cox, 1993; Newman et al., 2006). However, much of this past research has looked at CRF performance and nutrient leaching on a macro-scale, or throughout a production season (i.e., months to years, depending on the crop) and has not addressed the micro-scale nuances that contribute to the actual load of nutrients that are leached during individual irrigation events. Developing this knowledge of the physical and chemical factors that affect solute transport during irrigation may allow for the improvement crop management practices recent models (Majsztrik, 2011) that predict how changes in crop management practices will impact factors such as fertilizer use efficiency.

Solute transport

An understanding of how dissolved fertilizer salts (solutes) move through the pine-bark bark substrates used in the production of containerized ornamental crops is fundamental to reducing the quantity of agrichemicals leached from nursery containers during irrigation. Current theories of water and solute transport are largely based the body of research conducted on soil-based systems (Beven and Germann, 2013; Keller et al., 2004; Liu et al., 2010; Mohammadi et al., 2009; Russo, 1993), that provide a foundation on which current theories on solute transport in soilless substrates are built. However, a direct characterization of water and solute transport through the soilless substrate components used in nursery production is warranted.

Pine-bark substrates. The physiochemical properties of the pine-bark based soilless substrates commonly used in the Mid-Atlantic and southeastern U. S. nursery industry for the production of woody ornamentals consist of predominately large, low-density, organic material (such as pine-bark). The result is a highly porous substrate of low bulk density and nutrient holding capacity. However, despite these differences in physical and chemical properties, horticulturists have conducted only limited research that seeks to bridge the gap between what we know about solute transport in soils and that of soilless substrates.

Brown and Pokorny (1977) demonstrated that soluble potassium (K), when applied to the top of a pine-bark column, resulted in K adsorption to the bark, and that the distribution of adsorbed K was uneven throughout the column (most was retained in the upper portion). Furthermore, they demonstrated that an increase in pH led to an increase in the amount of adsorbed K, indicating the presence of pH dependent functional groups, which has been confirmed in several later studies (Daniels and Wright, 1988; Foster et al., 1983). Foster et al. (1983) applied deionized (DI) water to pine-bark columns (3.8 x 15 cm) that had been pre-treated with a NH_4NO_3 solution and found that the majority of both NH_4 and NO_3 were leached with 120 mL of DI water, which is slightly less than the total volume of the column. With the exception of Brown and Pokorny (1977), no other studies were solely focused on anion or cation transport, or reported complete physical properties, making interpretation and comparison with other studies difficult.

Studies on effluent volume in relation to leached nutrient load provide some information on the composition of the pore water solution before irrigation. Reduced leachate volumes have been associated with a reduced total load of nutrients leached (Owen et al., 2008; Tyler et al., 1996), which suggests that with lower degrees of leaching, smaller portions of the leachable nutrients in the substrate solution are leached. Additionally, Niemiera and Leda (1993) found similar results with regard to total nutrient load leached, but also reported that NO_3 and NH_4 concentrations in the substrate solution, as indicated by a pour through (PT) procedure, were higher at reduced LFs, which speaks to a greater residual, unleached nutrient load in the substrate solution after irrigation. Collectively, these findings suggest that before irrigation, an initially high, CRF-derived nutrient concentration resides in the pore-water solution and is flushed out to an extent that is dependent on the volume of water applied and subsequently leached. However, the mechanisms behind this nutrient leaching and leachate volume relationship, and how solutes move from the substrate solution and leave a container during irrigation are not understood.

Preferential flow. The concept of preferential flow refers to the flow of water through select pathways in the soil or substrate. Selker (1996) provided recommendations for applying preferential flow concepts to horticultural field production, and in doing so, summarized the three types of preferential flow. Fingered flow occurs in coarse textured, unstructured soils (sands) and results in uneven flow paths (i.e., fingers) of water. Finger width is known to widen with increased antecedent soil moisture content (MC) (Liu et al., 1994). Macropore flow is associated with highly structured soils where water preferentially flows through large pores. These pores are often associated with shrink/swell soils, decomposed root channels, worm holes or animal burrows. Lastly, funnel flow occurs in soils comprised of different textural layers, and consequently different hydraulic conductivities, which redirect or funnel water to select paths. Funnel flow is less applicable to the production of containerized plant production in soilless substrates due to the relative textural uniformity within a single container. Therefore, due to the highly porous nature of soilless substrates (Drzal et al., 1999), preferential flow is most likely attributed to finger or macropore flow. Furthermore, if these flow phenomena occur in soilless substrates, their occurrence would affect the leaching of nutrients during the application of irrigation water.

Root growth. An understanding of how water flows through a bark-based substrate also necessitates an investigation of the effect of root growth on water movement. Altland et al. (2011) demonstrated that plant roots will decrease air space (AS) and increase container capacity (CC), an effect attributed to roots that grow into and occupy pore spaces, as well as the decomposition of organic substrate components. Gish and Jury (1983) observed that infiltrating a chloride tracer solution through columns containing loamy sand, under steady-state flow conditions, moved through the column with less dispersion in treatments containing a wheat plant than a fallow column. They postulated that roots grew into large pore spaces and effectively created a homogenous pore size distribution that reduced the preferential flow of water through large pores and created a more uniform network of flow paths. However, their experiments were conducted under steady-state flow conditions (i.e., a steady flow of water was passed through the column at a consistent moisture content), in contrast to irrigation, where water is applied to a dry soil or substrate. Nash and Laiche (1981) assessed the hydraulic conductivity of ryegrass grown in various horticultural substrates comprised of bark, peat and sand. They reported very high and erratic hydraulic conductivity values in combination with a root growth distribution that was concentrated at the substrate surface and along container walls. They theorized that this root distribution may cause channeling along container walls and lead to localized high hydraulic conductivity. However, a more direct observation of channeling and preferential flow would be useful when developing BMPs that maximize irrigation and fertilizer efficiency.

Significance

Characterizing the fundamental principles of how water and solutes flow through the soilless substrates during the application of irrigation water may lead to the improvement of irrigation and fertilizer management recommendations. Furthermore, models that predict nutrient leaching as affected by the manipulation of certain production factors (i.e., fertilizer rate, placement, irrigation duration, etc.) may be improved using the basic principles of solute transport that occur during irrigation. This body of research may also serve as a foundation for future studies that enhance our understanding of solute transport mechanisms during irrigation.

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Chapter 2

Water Movement Through a Pine-bark Substrate During Irrigation

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Water Movement Through a Pine-bark Substrate During Irrigation

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Subject Category: Soil management, fertilization, and irrigation.

Water Movement Through a Pine-bark Substrate During Irrigation

Additional index words. Leachate, preferential flow, root growth, solute transport, wetting front.

Abstract. Regulatory and economic incentives to improve water and fertilizer use efficiency have prompted the nursery industry to seek new and advanced techniques for managing the production of ornamental crops. The development of best management practices, especially with regard to fertilizer and irrigation management, is largely based on research that looks at season-long trends in water and nutrient use. Little effort has been placed on understanding how irrigation water moves through a substrate during a single irrigation event. Developing this knowledge may allow for the refinement of recommended best management practices that improve water and fertilizer use efficiency. Therefore, a study was conducted to characterize the movement of irrigation water (4, 9 and 17 weeks after transplanting; WAT) throughout the production cycle of *Ilex crenata* Thunb. 'Bennett's Compactum' plants that were container-grown in a bark-based substrate alongside fallow (i.e., without a plant) containers. Tensiometers were placed throughout the substrate profile to detect changes in bark water status, via matric potential (ψ; kPa), during individual irrigations. At 4 WAT, the pre-irrigation ψ in the upper substrate profile was 12.3 times more negative (i.e., drier) than the substrate near the containers base, and 6.0 times more negative than the middle of the container. This gradient was decreased at 9 and 17 WAT, as roots grew into the lower portion of the substrate profile. Water began to drain from the base of the container, on average, 59.9 sec. ± 1.0 SE after irrigation commencement for fallow

containers and 35.7 seconds ± 1.3 SE for plant-containing treatments, indicating a tendency for water to channel through the substrate in plant-containing treatments, where plant water uptake induced a gradient in the substrates pre-irrigation moisture distribution (i.e., portions of the substrate profile were relatively dry where plant roots had taken up water). Consequently, the application of fertilizer via irrigation water (i.e., fertigation) has the potential to be highly inefficient if applied under dry substrate conditions that may lead to channeling. Therefore, fertigation should occur when the substrate moisture content (MC) in the upper portion of the container is higher than the pre-irrigation MCs observed in this study to minimize the occurrence of channeling. The effect of root growth should also be taken into account when seeking the proper balance between pre-irrigation substrate MC and irrigation application rate to reduce the risk of unwanted channeling.

INTRODUCTION

Minimizing the load of mineral nutrients that are leached from containerized crops is a goal of both horticultural scientists and members of the industry for two reasons. First, leached mineral nutrients are no longer available for crop growth, and improvements in fertilizer use efficiency may help growers maintain profitability as fertilizer costs increase. Secondly, reducing the runoff nutrient load minimizes non-point source agrichemical contributions to local watersheds while simultaneously helping growers to comply with current or future regulatory standards, such as the total maximum daily load (TMDL) limits for agrichemical contributions to the Chesapeake Bay watershed (Majsztrik and Lea-Cox, 2013). A set of best management practices (BMPs) (Bilderback et al., 2013) are available to growers as a toolset that can be used to improve water- and nutrient-use efficiency of containerized ornamental crops. The industry has responded positively, as indicated by generally favorable BMP adoption rates in regional and national surveys of major nursery crop production regions in the United States (Garber et al., 2002; Mangiafico et al., 2010; Schoene et al., 2006).

Among these BMPs are the use of controlled-release fertilizers (CRFs) and nutrient monitoring techniques. A recent nation-wide survey reported that 66.4% of nurseries were currently using CRFs (Dennis et al., 2010), a fertilizer technology that has been shown to be effective in in reducing nitrogen (N) and phosphorus (P) runoff as compared to fertigation (Wilson and Albano, 2011).

CRF performance is well understood as a result of season-long (≈ 4 to 12 mo.) studies (Broschat and Moore, 2007; Cabrera, 1997) that use techniques like the pour-through (PT) procedure or effluent (leachate) collection to evaluate trends in nutrient release. This knowledge enables growers to make informed decisions regarding irrigation and fertilizer management in an effort to improve crop quality and reduce nutrient loss through leaching. However, considerably less is known about nutrient leaching trends on a short time scale, i.e., how water and fertilizers move through and leach from a soilless substrate *during* irrigation. Developing this knowledge may allow for the refinement of production practices (e.g., irrigation, fertilizer use, substrate selection, etc.) that lead to improved water and nutrient use efficiency.

Research on the movement of water and solute transport in soils (Beven and Germann, 2013; Mohammadi et al., 2009; Russo, 1993) provides a good foundation for understanding soilless systems. However, the physical properties of soilless substrates are quite different from field soils. The physical properties of the pine-bark and sand blends commonly used in the Mid-Atlantic and southeastern United States nursery industry for the production of woody ornamentals (similar to the substrate used in this study) consists of predominately large, low-density, organic material. Consequently, substrates are highly porous and of low bulk density (Drzal et al., 1999). However, despite these key differences in physical properties, little research has been devoted to understanding how water moves through these substrates when applied during irrigation. Therefore, characterizing how water moves through soilless substrates during irrigation is warranted, as it may lead to improved production practices that maximize water application efficiency (WAE; i.e., substrate retention of applied water).

An understanding of how water flows through a bark-based substrate also necessitates an investigation of the effect of root growth on water movement. Altland et al. (2011) demonstrated that plant roots will decrease air space (AS) and increase container capacity (CC), an effect that has been attributed to roots growing into and occupying pore spaces, as well as the decomposition of organic substrate components. Gish and Jury (1983) observed that in loamy sand columns, an infiltrating chloride tracer solution applied to columns under pre-established, steady-state flow conditions, moved through the column with less dispersion (i.e., more evenly) in treatments containing a wheat plant than a fallow column. They postulated that roots grew into large pore spaces and effectively created a homogenous pore size distribution that reduced the preferential flow of water through large pores and created a more uniform network of flow paths. However, their experiments were conducted under steady-state flow conditions, not under irrigation conditions, i.e., water applied to a dry soil or substrate. Nash and Laiche (1981) assessed the hydraulic conductivity (HC) of water moving through bark, peat and sand-based horticultural substrates that ryegrass was grown. They reported high and variable hydraulic conductivities (HCs) that generally ranged from 1.0 to 4.5 $cm \bullet min^{-1}$ and extreme cases where HC was reported to be 26 $cm \bullet min^{-1}$. They theorized that roots that were concentrated near the substrate surface and along container walls may have caused channeling along container walls and lead to localized high HC values. Johnson and Lehmann (2006) discussed how, in shrink-swell soils, live roots that compress adjacent soil and decomposed roots allow for the preferential flow of infiltrating water through root-generated paths. However, a more direct observation of how root growth affects the channeling of irrigation water through preferential flow paths in the low density, porous soilless substrates used in containerized plant production would be useful when developing BMPs that maximize irrigation and fertilizer efficiency.

This research is focused on characterizing the movement of irrigation water throughout a 17-week production cycle, using *Ilex crenata* Thunb. ‘Bennett’s Compactum’ grown in 2.7 L nursery containers and a bark-based substrate. The objectives of this study were 1) to evaluate the patterns in which water moves through a pine-bark based substrate at different depths in the container profile and 2) to determine the subsequent effect of root growth on water movement.

MATERIALS AND METHODS

Experimental Design. On 29 May, 2013, two uniform *Ilex crenata* 'Bennett's Compactum' liners (substrate removed from roots) were potted into 2.7 L; 17.8 cm tall, 15.7 cm upper diameter nursery containers (Myers industries, Middlefield, OH) using a 9 part bark:1 part sand (by vol.) substrate amended with 1.8 kg•m^{-3} crushed dolomitic lime (Rockydale Quarries Corp., Roanoke, VA) and 1.8 kg•m^{-3} pelletized dolomitic lime (Kelly's Limestone LLC., Kirksville, MO). The physical properties (Table 1) were determined using the North Carolina State University porometer procedure (Fonteno, 2003). Particle size distribution (percent by weight), as determined by a 5-minute mechanical agitation with oven-dried substrate, was as follows: > 6.3 mm = 8.0; 6.3 to 2 mm = 27.6; 2 to 0.71 mm = 37.9; < 0.71 mm = 26.5. Each container was topdressed with 9 g of a 5 to 6 month, 16N–2.6P–9.1K; 7.9% N–NO_3, 8.4% N–NH_4 + micronutrient CRF (Harrell's, Lakeland, FL). Beginning 10 weeks after transplanting (WAT), all remaining plants were liquid fed weekly with 200 mL of a 238 mg•L^{-1} N solution of Peters 20-20-20 (JR Peters Inc., Allentown, PA) to promote additional growth. Fallow containers (i.e., containing no plant) were also potted as a control. At potting, all plants were pruned to a uniform baseline canopy architecture (height = 14 cm ± 0.9 SE; width = 14.6 ± 1.1 SE; perpendicular width = 12.4 cm ± 1.3 SE; n = 5). Plants were grown in an outdoor gravel bed at the Hampton Roads Agricultural Research and Extension Center in Virginia Beach, VA. All treatments received overhead irrigation (1.27 cm•hr.$^{-3}$) every other day and were managed to reach a target leaching fraction (LF = vol. leached / vol. applied) of 0.1.

Data were collected at three harvest intervals throughout the season, 4, 9 and 17 WAT. Due to the effect of canopy architecture on irrigation water interception (Million et al., 2010), all plants were pruned to a width and height of 15.7 cm (container diameter) one week before each harvest interval to minimize any impact of canopy architecture on water application rate or volume. At each harvest interval 15 containers were brought indoors and the substrate was allowed to dry to an average, gravimetrically determined, volumetric water content (VWC) of 31.9% ± 0.004 SE (n = 60). After reaching the target VWC, each container was prepared for irrigation in a custom irrigation platform (Fig. 1), during which substrate matric potential (ψ) and the time which drainage began was measured. Of the 15 containers used at each harvest interval, ψ was measured at one of three heights in the container profile (five reps per height): upper, mid and low height (12.7, 7.6 and 2.5 cm from the container base, respectively). At each profile height, five T5 tensiometers (UMS, Munich, Germany) were horizontally placed every 72 degrees around the circumference of that container (Fig.2) and were inserted to a specified depth (Table 2) that varied proportionately with the taper of the container, but were evenly distributed between the center of the container and the wall at each height. Each container was prepared for tensiometer installation by drilling a 5 mm hole in the container wall and boring a horizontal pilot hole into the substrate using a bore provided by UMS with the tensiometers. All holes were bored 5 mm short of the final sensor installation depth (Table 2). This method left 5 mm of minimally altered substrate in which the tensiometer tip would nest, improving sensor contact with the substrate. Containers were then placed in the irrigation platform and tensiometers were inserted into the substrate and connected to a CR3000 datalogger and AM16/32A multiplexer (Campbell Scientific, Inc., Logan, UT) programmed to collect one measurement from each sensor every second. After installation, tensiometers were allowed to equilibrate until they provided a steady baseline measurement, at which point containers were irrigated with deionized water through a diffuser mounted 27 cm above the substrate surface. Irrigation was applied at a rate of 300 ml•min^{-1}, which is comparable to a 19 L•hr^{-1} spray stake but inherently faster that most overhead irrigation systems. Irrigation ended once the output from all five tensiometers had increased from the negative, pre-irrigation baseline ψ, to a stable ψ near 0 kPa, indicating water had arrived at each tensiometer.

After data collection, shoots were removed at the substrate surface and the substrate was carefully removed to measure the depth of roots in the substrate profile (Table 3). Remaining substrate was then removed by washing roots. Root and shoot tissue were dried to a constant weight at 60° C (Table 3).

Data Analysis. The experiment was a 4 (sampling interval) x 3 (height of sensor placement in container profile) factorial, with 5 horizontal sensor insertion depths within each profile height, using a completely randomized design with five replicates. The datalogger output for individual tensiometers (Fig. 3), where the ψ measurements were plotted against the time (s) after irrigation began, was used to assess the moisture distribution throughout the container and determine the time at which water arrived at individual sensors. Moisture distribution was assessed using the matric potential at the time irrigation began (ψ_o). For the vertical moisture distribution, ψ_o from all five sensors at either the low, mid or upper profile heights (2.5, 7.6 or 12.7 cm respectively) were pooled. As shown in Fig. 3, the time (seconds after commencement of irrigation) which water arrived at individual tensiometers was calculated using a procedure adapted from Germann and Hensel (2006) in which a linear regression line was fitted to the baseline ψ, and a second line was fitted to the slope induced by water arrival. The intersection of these two lines was considered the time which water arrived at a given sensor. Additionally, the time at which water was first observed to drain from containers during irrigation was also recorded. These arrival times (tensiometer and drainage) were normalized by converting to a rate by dividing the linear distance that water would travel (substrate surface to tensiometer or container base) by the time it was calculated to arrive at a given location. These rates were compared at different locations in the container and allowed the authors to make inferences about water movement at different locations throughout the container.

Moisture distribution and the calculated rate of water arrival data were subjected to analysis of variance ($\alpha = 0.1$) (Marini, 1999) and means separation by way of Tukey's HSD or Tukey-Kramer's. All data were processed using JMP® Pro version 10.0.2 (SAS Institute Inc., Carey, NC).

RESULTS AND DISCUSSION

Moisture distribution. Analysis of ψ prior to the onset of irrigation reveals a vertically distributed moisture gradient, where the substrate is driest at the top of the container and wettest at the base (Table 4), confirming trends observed by Owen and Altland (2008). This gradient (Table 5; presented as a ψ ratio between different profile heights) is of greatest magnitude between the upper and lower profile heights (12.7 and 2.5 cm from container base, respectively) at 4 WAT. A similar trend was observed between the upper and mid (7.60 cm from container base) profile heights, though the magnitude of these gradients is less than the observed gradient between upper and low profile heights. A much smaller moisture gradient was observed in the fallow treatment (0 WAT) and is likely due to the combined effect of surface evaporation and the pooling of gravitational water in the base of the container. The moisture distribution of plant containing treatments (4, 9 and 17 WAT) followed general trends in root growth. At 4 WAT, roots had grown to a sub-surface depth 8.89 cm (Table 3). Consequently, most of the plant-water uptake occurred above this 8.89 cm root depth, leading to a concentrated dry region in the upper substrate profile and a steeper observed moisture gradient than at 9 or 17 WAT. As roots grew deeper into the substrate at 9 and 17 WAT, the total portion of the substrate profile that water was taken up by the plant had expanded, and the moisture gradient between the relatively dry upper regions and relatively wet lower regions decreased. This indicates that a seasonal increase in root depth (and proportionate root mass) was associated with a more uniform pattern of water uptake throughout the containers vertical profile.

There was only a minimal horizontal moisture gradient at each vertical profile height (data not shown). Differences were only observed at the upper profile height during the early (4 WAT) and mid-season (9 WAT) harvest intervals. Here, the substrate was driest in the center of the container and wetter near the container wall. Though not measured, lateral root distribution and subsequent pattern in water uptake possibly caused this phenomenon, similar to how root depth affected the aforementioned vertical moisture distribution.

Wetting front movement. Water was observed to begin draining from the base of containers 59.9 sec. ± 1.0 SE and 35.7 seconds ± 1.3 SE after irrigation commencement for fallow and plant-containing (pooled average of 4, 9 and 17 WAT) treatments, respectively. The observed drainage times contributed to the fastest calculated rate of water movement occurring at the base of the container (based on the time which water was first observed to drain) for each plant-containing treatment (4, 9 and 17 WAT), with the exception of 4 WAT at the low profile height where the calculated rate was similar to the rate at the container base (Table 4). In comparison, there were no differences in the calculated rate of water movement between any of the profile heights and the container base for the fallow (0 WAT) treatment (Table 4). Collectively, these findings suggest that water channeled through the substrate or along container walls in plant-containing treatments and progressed somewhat evenly through the substrate of fallow treatment.

Between the upper, mid and lower profile heights of each plant-containing treatment (4, 9 and 17 WAT), the rate of water movement was calculated to be highest in the lower profile and lowest in the upper profile (Table 4). This general trend persisted throughout the season. Initially, these differences in the calculated rates of water movement may seem counterintuitive. However, the relationship between substrate moisture content (MC) and the width and speed of an infiltrating finger (channel of water) may help to explain these findings. Bauters et al. (2000) and Liu et al. (1994) demonstrated that, in sands, an infiltrating finger or channel of water will be relatively narrow and fast-moving at low MCs and will be relatively wide and slow-moving at high MCs. Applied to the findings of this study, it is likely that in the upper portion of the container profile, where the substrate is relatively dry, narrow and fast-moving channels develop that may bypass the tensiometers at that height. When that channel subsequently reaches the lower, relatively wet profile heights, it becomes more diffuse and progresses slowly.

For a bypassed, upper-profile tensiometer to detect the arrival of water, it would then require a secondary mechanism. Such possibilities include 1) the formation of a new channel that directly contacts the tensiometer, 2) lateral redistribution of water from an adjacent channel or 3) backfilling from a lower region in the container profile that begins after a channel has reached the base of the container. In any of these scenarios, the original channel or finger may cross the horizontal plane at the upper profile height before water reaches the tensiometer via one of the secondary mechanisms at a later time. The net effect is an inflation of the denominator (time) in the rate of water movement calculation, hence a slower calculated rate in the upper profile. These fast-moving channels in the upper profile would likely reach the lower substrate profile heights quickly, where they are likely to be more diffuse and make contact with tensiometers more evenly.

The observed seasonal increase in root growth and the subsequent change in moisture distribution throughout between plant containing treatments did not impact the previously discussed patterns of water movement (inferred from calculated water velocities) at any of the profile heights. The most substantial difference was between the fallow and any plant-containing treatment. However, even though roots had grown to the full substrate depth by the end of the study, roots had not totally occupied the entire substrate volume, hence the state of the container was not considered pot-bound after 17 weeks. Allowing more time for roots to proliferate in the lower profile heights may have a meaningful impact on water movement in future studies with regard to crops late in their production cycle.

CONCLUSIONS

The results of this study demonstrate the ease in which water can channel through nursery containers under our experimental conditions. Irrigation water may channel through portions of the substrate, leading to an uneven post-irrigation water distribution and unnecessary loss of water and leaching of dissolved fertilizer salts. This may be of increasing concern when applying fertilizer via irrigation water (i.e., fertigation), as applied fertilizers may quickly leach from a substrate and not reach the entire root zone. If a crop is to be fertigated, it would be most effective to do so when the substrate is at or near CC and to apply only the quantity of water needed to displace the volume of water held by the substrate at CC.

Due to the impact of root growth on water uptake and the subsequent pre-irrigation substrate moisture distribution at different times throughout a production season, caution should be exercised when using substrate weight as an indicator of when to irrigate a newly planted crop. If the lower portion of a substrate profile is at a high MC, the container may still be heavy despite the need to irrigate the upper profile, where the roots reside.

This research raises questions about irrigation management with regards to application method, application rate and substrate MC at the time of irrigation. Applying water at a high rate to a dry substrate may lead to unnecessary leaching of water and nutrients. Therefore, additional research is warranted to determine the optimal balance between MC and water application rate to minimize leaching without perpetually keeping the substrate too wet. If a crop is to be irrigated when dry, the use of cyclic irrigation may reduce the risk of unwanted leaching. The first cycle may channel through a portion of the substrate, but can laterally diffuse between cycles to reduce the amount of channeling that occurs in later cycles. Lastly, the use of surfactants deserves additional research to determine if their use may increase the width of a channel infiltrating through a dry substrate and improve wetting efficiency.

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TABLES

Table 1. Physical properties for a substrate comprised of 9 parts pine-bark and 1 part sand (by vol.).

D_b	TP	CC	AS
0.325	78.7	52.3	26.4

D_b = Bulk density; g•cc^{-1}

TP = Total porosity. Percent of substrate vol. comprised of pores.

CC = Container capacity. Percent of substrate vol. comprised of water after free drainage.

AS = Air space. Percent of substrate vol. comprised of air at CC.

Table 2. Tensiometer insertion depths (cm from the center of the horizontal container profile) at each height in the vertical container profile.

Vertical position[y]	Sensor position[z]					Container radius[x]
	1	2	3	4	5	
Upper (12.7 cm)	0.0	1.5	2.9	4.4	5.8	7.1
Mid (7.6 cm)	0.0	1.4	2.7	4.1	5.4	6.7
Low (2.5 cm)	0.0	1.3	2.5	3.8	5.0	6.3

[z]Positions correspond to those in Figure 2b.

[y]Distance from the base of the container.

[x]Container radius differs at each vertical profile height due to the taper of the container and determines the horizontal distribution of the sensors at the given vertical profile height.

Table 3. Root length and dry weight of *Ilex crenata* 'Bennett's Compactum' grown in a 2.7 L nursery container throughout a 17 week period.

WAT[z]	Root depth (cm)	Root dry-weight (g)
4	8.89 a[y]	1.61 a
9	12.11 b	3.08 b
17	14.67 c	6.26 c

[z]WAT = weeks after transplant. The 0 WAT treatment is not included as this treatment is for fallow containers.

[y]Means within column not sharing the same letter are significantly different using Tukey's HSD ($P \leq 0.1$).

Table 4. Substrate matric potential at the onset of irrigation (ψ_o; kPa) and calculated rate of water movement (v; cm•s^{-1}) at four different heights along the vertical profile of a 2.7 L nursery container throughout a 17 week period.

Distance from base (cm)	Production phase (WAT[z]) of *Ilex crenata* 'Bennett's Compactum'							
	0[y]		4		9		17	
	ψ_o	v	ψ_o	v	ψ_o	v	ψ_o	v
12.70	-6.44 a A[x]	0.23 a	-23.28 b A	0.13 b A	-22.92 b A	0.13 b A	-27.67 b A	0.13 b A
7.62	-3.97 a B	0.24	-4.05 a B	0.24 AB	-11.08 b B	0.23 B	-17.59 c B	0.21 B
2.54	-2.47 a C	0.20 a	-1.84 a B	0.34 b BC	-6.07 b C	0.29 ab B	-13.85 c C	0.28 ab B
0.00[w]	----	0.25 a	----	0.48 b C	----	0.42 b C	----	0.44 b C

[z]Weeks after transplant.

[y]0 WAT signifies a fallow container.

[x]ψ or v means not sharing the same lower-case letter within rows, or upper-case letters within columns, are significantly different according to Tukey-Kramer's HSD ($P < 0.1$). Any row or column without the respective lower or upper-case letter indicates no significant differences between means.

[w]Base of container; ψ not measured at container base; v is based on the time at which drainage began.

Table 5. Matric potential ratios between the top, mid and low (12.7, 7.6 and 2.5 cm from container base respectively) profile heights for *Ilex crenata* 'Bennett's Compactum' grown in a 2.7 L nursery container throughout a 17 week period.

	Profile height comparison		
WAT^{z}	upper vs. low	upper vs. mid	mid vs. low
0^{y}	2.8 A a^{x}	1.7 A b	1.8 b
4	12.3 B a	6.0 B b	2.0 b
9	4.5 A a	2.6 A b	2.2 b
17	2.1 A a	2.1 A ab	1.4 b

^{z}Weeks after transplant.

^{y}0 WAT signifies a fallow container.

^{x}Means not sharing the same lower-case letter within row, or upper-case letter within column, are significantly different according to Tukey's HSD ($P \leq 0.1$). Any row or column without the respective lower or upper-case letter indicates no significant differences between means.

FIGURES

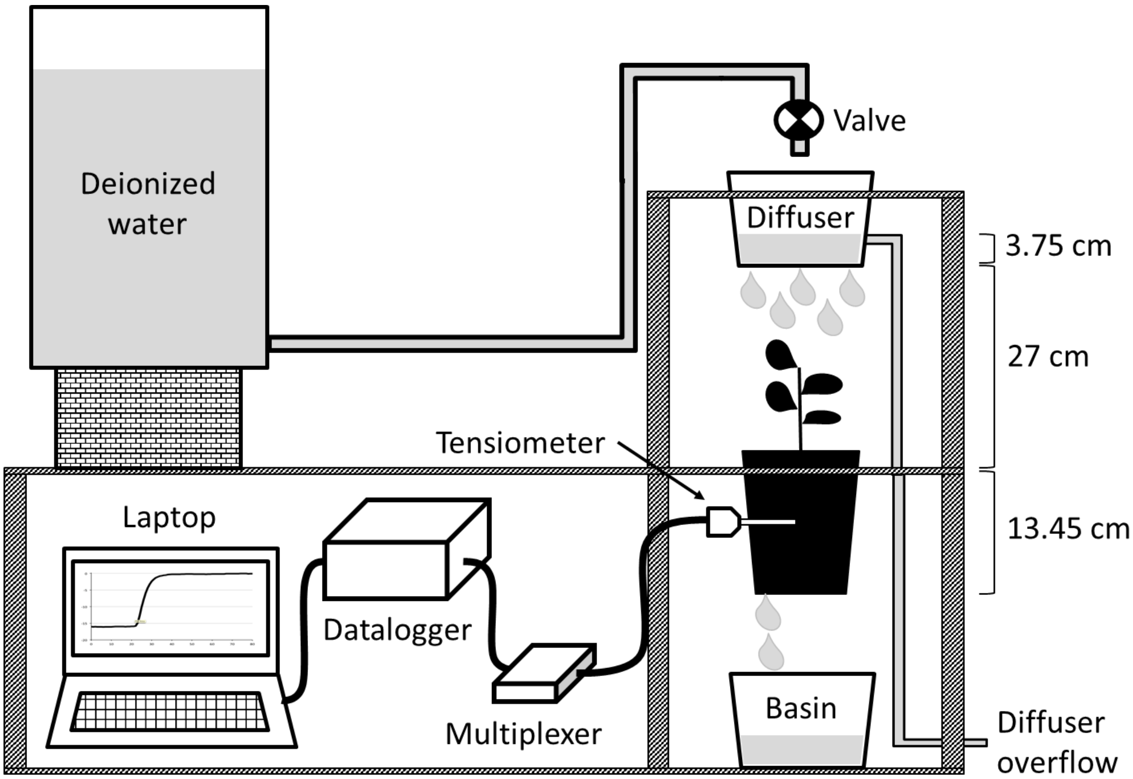

Fig. 1. Physical setup of the irrigation platform depicting the application of deionized irrigation water through a diffuser and the flow of real-time substrate matric potential data from tensiometers to a laptop.

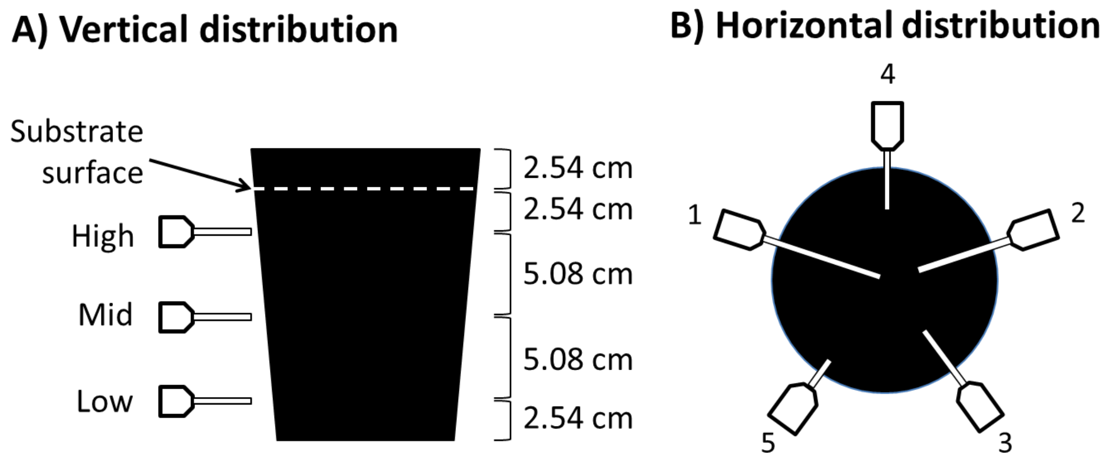

Fig. 2. a) Distribution of tensiometers in the vertical container profile relative to the container size and substrate level. b) Overhead view of a container showing the horizontal distribution of tensiometers. Insertion depths correspond to those stated in Table 2.

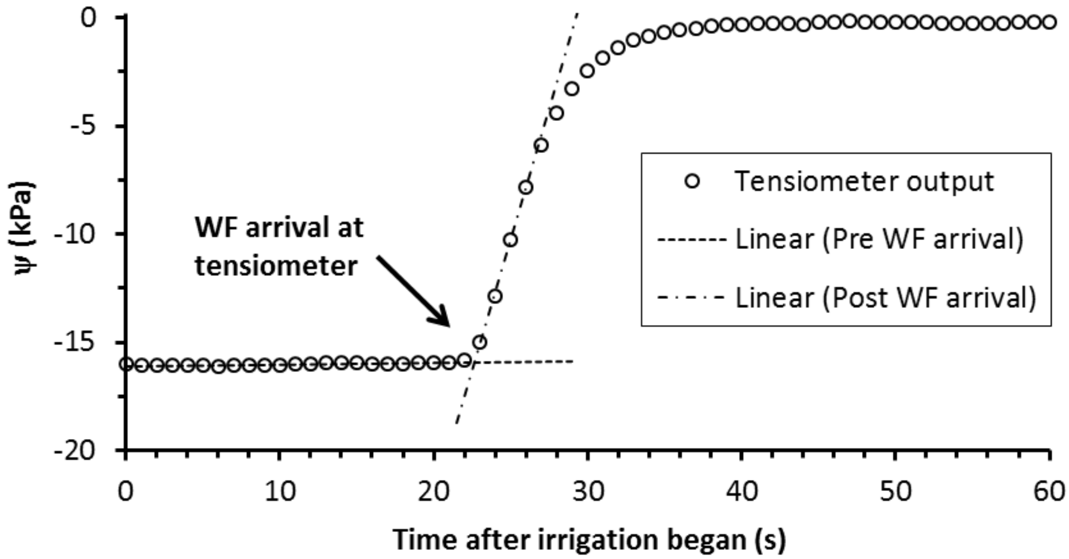

Fig. 3. Example of how substrate matric potential at the time when irrigation began (ψ_o) and wetting front (WF) arrival are determined. ψ_o is based on the first ψ measurement (i.e., time = 0s). WF arrival is calculated from the intersection of the pre and post WF arrival linear regressions. In this case, the WF arrives 23s after irrigation began.

Chapter 3

Solute transport through a pine-bark based substrate under saturated and unsaturated conditions

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Solute transport through a pine-bark based substrate under saturated and unsaturated conditions

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Subject Category: Soil management, fertilization, and irrigation.

Solute transport through a pine-bark based substrate under saturated and unsaturated conditions

Additional index words. Breakthrough curve, cation exchange capacity, containerized crops, nitrate, phosphate, potassium

Abstract. An understanding of the how dissolved mineral nutrient ions (solutes) move through a pine-bark substrate during the application of irrigation water is vital to better understanding nutrient transport and leaching from containerized ornamental crops during an irrigation event. However, current theories on solute transport mechanisms in soilless systems are largely based on research in mineral soils and thus fail to explain processes in soilless substrates. A study was conducted to characterize the fundamental principles of how solutes are transported through a pine-bark substrate by developing and analyzing breakthrough curves (BTCs). Columns filled with a pine-bark substrate were subjected to application of a nutrient solution (tracer) and deionized (DI) water under saturated (air is displaced from substrate pores) and unsaturated (air remains in substrate pores) conditions. Effluent that drained from the columns during these applications was collected and analyzed to determine the effluent concentration (C) of the bulk ions in solution via electrical conductivity (EC), nitrate (NO_3^-), phosphate (PO_4^{3-}) and potassium (K^+). The BTCs were developed by plotting C relative to the concentration of the input solution (C_o) (i.e., relative concentration = C/C_o) as a function of the cumulative effluent volume. Solutes broke through the column earlier (i.e., with less cumulative effluent) and occurred more abruptly (a quicker transition from C/C_o = 0 to 1) under unsaturated than saturated conditions. Movement

of the anions, NO_3^- and PO_4^{3-}, through the substrate occurred more quickly than the cation K^+. Throughout the experiment, 37% of the applied K^+ was retained by the pine-bark. The adsorption of K^+'s to pine-bark cation exchange sites displaced calcium (Ca^{2+}) and magnesium (Mg^{2+}), of which the combined equivalent charge accounted for 43.1% of the retained K^+. These results demonstrate the relative ease that negatively charged fertilizer ions can move through a pine-bark substrate while solution is actively flowing through substrate pores, such as during irrigation. This approach to evaluating solute transport may be used in horticultural research to better understand how mineral nutrients move through and subsequently leach from soilless substrates during irrigation. Expanding this knowledge base may lead to the refinement of production practices that improve nutrient and water use efficiency in container nurseries.

INTRODUCTION

An understanding of how dissolved mineral nutrient salts (i.e., solutes) move through the pine-bark substrates used in the production of containerized ornamental crops is fundamental to reducing the quantity of fertilizers leached from nursery containers during irrigation. Significant effort has been placed on understanding the leaching of mineral nutrients on a large time-scale (i.e., throughout a production season; approx. 4 to 12 mo.), in which controlled-release fertilizers (CRFs), a currently recommended best management practice (BMP; Bilderback et al., 2013), are used as the nutrient delivery method (Alam et al., 2009; Cabrera, 1997, Colangelo and Brand, 2001; Cox, 1993; Newman et al., 2006). The release of mineral nutrients from CRFs is often cited to be a function of temperature (Adams et al., 2013; Husby et al., 2003), and a predictor of the quantity of nutrients released into the substrate solution. This nutrient load in the substrate solution has the potential to leach. However, the actual nutrient load that is leached is a function both the quantity of pre-irrigation, leachable nutrients in the substrate solution and the physiochemical properties of the substrate that affect the transport of solutes while water is being applied to the substrate (i.e., irrigation or rainfall). Expanding our knowledge of the physiochemical factors that affect solute transport during irrigation may allow practitioners to better manage applied agrichemicals and provide data to help improve recent crop management models (Majsztrik, 2011) in order to better predict fertilizer use efficiency.

Research on how water and solutes move through soil-based systems (Beven and Germann, 2013; Keller et al., 2004; Liu et al., 2010; Mohammadi et al., 2009) provides a foundation on which current theories of solute transport in soilless substrates are built. However, the physochemical properties of mineral soils may be quite different than that of soilless substrates, which compared to mineral soils are more porous (approx. 75% total porosity for the pine-bark / sand blend used in this study), have lower bulk density, and are comprised mainly of organic matter. Hoskins (2014) demonstrated that during irrigation, water has the tendency to preferentially flow through portions of a pine-bark substrate, a process that is affected by substrate moisture content. However, there is limited information that bridges the gap between what we know about solute (fertilizer ion) transport in soils to that of soilless substrates.

Brown and Pokorny (1977) reported that soluble potassium (K^+), when applied to the top of a pine-bark column resulted in K^+ adsorption to the bark, and that the distribution of that adsorbed K was uneven throughout the column (most was retained in the upper portion). Furthermore, they demonstrated that an increase in pH led to an increase in the amount of adsorbed K^+, indicating the presence of pH dependent functional groups, which has been confirmed in several later studies (Daniels and Wright, 1988; Foster et al., 1983). Foster et al. (1983) applied deionized (DI) water to pine-bark filled columns (3.8 x 15 cm) that had been pre-treated with a NH_4NO_3 solution and found that the majority of both NH_4^+ and NO_3^- were leached with 120 mL of DI water, which was slightly less than the total volume of their column. With the exception of Brown and Pokorny (1977), no other studies were solely focused on anion or cation transport or reported complete substrate physical properties, making interpretation and comparison with other studies difficult.

Developing breakthrough curves (BTCs) can provide valuable information about the physiochemical properties of the substrates used in containerized plant production and how they affect solute transport during irrigation. A BTC is a plot of the relative effluent solute concentration vs. time or cumulative discharge (Hillel, 2004). Typically, a solution containing tracer ions of known initial concentration (C_o) is applied to a soil or substrate filled column, while the effluent that drains from the column is collected and analyzed to determine the concentration of the tracer (C). The shape of the resulting BTC provides information about how the tracer was transported through the substrate. As the tracer solution enters the substrate, it interacts with the solution that is already in the pores at a "boundary" or "front." In an ideal system, the front may behave as a sharp boundary where there is no mixing of the applied tracer solution and the antecedent pore water. This front progresses evenly and unaltered through the substrate like a piston through a cylinder (i.e., "piston flow"). Upon the displacement of all the pores (i.e., one pore volume; PV), the theoretical piston reaches the other end of the column and is reflected in the BTC by a sudden increase in the effluent tracer concentration (C/C_o changes from 0 to 1). However, what is more likely to occur is a certain degree of interaction or mixing between the tracer solution and the pre-existing pore water (via dispersion or diffusion), the extent of which is largely influenced by the physical and chemical properties of the substrate. This interaction will affect the shape of the BTC. In substrates where a high degree of dispersion and diffusion occur, the change from $C/C_o = 0$ to 1 will be a gradual process that occurs over a larger effluent volume than the piston flow model, where the transition is theoretically instantaneous.

The objective of this study was to develop BTCs for a pine-bark based substrate that is representative of the mid-Atlantic and Southeastern U.S. nursery industries for the production of containerized ornamental crops. Breakthrough curves were generated under saturated and unsaturated conditions, with several mineral nutrient ions as tracers that varied in their potential for chemical interaction with the substrate. The resulting BTCs were interpreted and used to describe the behavior of reactive and non-reactive dissolved mineral nutrient ions in a pine-bark substrate.

MATERIALS AND METHODS

Anion and cation solute transport experiments (expt.) were conducted at the Virginia Tech Hampton Roads Agricultural Research and Extension Center (Virginia Beach, VA).

Substrate preparation and analysis. A 9 pine-bark:1 sand (by volume) substrate was amended with 1.8 $kg{\bullet}m^{-3}$ crushed dolomitic lime (Rockydale Quarries Corp., Roanoke, VA) and an equal rate of pelletized dolomitic lime (Kelly's Limestone LLC., Kirksville, MO). The substrate and was placed into 2.7 L (trade gallon) nursery containers (Myers Industries, Middlefield, OH). In the anion expt., containers were placed on an outdoor gravel pad receiving daily 15-minute overhead irrigation (12.7 $mm{\bullet}hr^{-1}$), and in the cation expt., in a greenhouse, where they were hand-watered on average, every other day until leaching was observed. The day before substrate (at this point, outdoors, in containers) was to be used in the experiment, the substrate for the anion or cation experiments was pooled into one composite sample and allowed to equilibrate overnight in a sealed container to ensure even moisture distribution prior to packing into columns. The same bark was used in both the saturated and unsaturated treatment of the anion expt. Particle size distribution (percent by weight), as determined by a 5-minute mechanical agitation with oven-dried substrate, was as follows for the cation expt.: > 6.3 mm = 8.0 ± 1.1 SE; 6.3 to 2 mm = 27.6 ± 1.1 SE; 2 to 0.71 mm = 37.9 ± 1.7 SE; < 0.71 mm = 26.5 ± 0.8 SE and for the anion expt.: > 6.3 mm = 7.0 ± 2.0 SE; 6.3 to 2 mm = 20.5 ± 1.5 SE; 2 to 0.71 mm = 38.8 ± 1.7 SE; < 0.71 mm = 33.7 ± 1.8 SE. The physical properties (Table 1) were determined using the NCSU porometer procedure (Fonteno, 2003). Cation exchange capacity (CEC) of the substrate was determined to be 110.7 $meq{\bullet}L^{-1}$ ± 3.5 SE using a method first described by Thorpe (1973) and modified by Altland et. al. (2014; in press).

Column preparation. Vertically oriented, acrylic columns (length = 30 cm; i.d. = 7.75 cm; o.d. = 8.9 cm; volume = 1.415 L) were packed with the previously described substrate using a modified version of the NCSU porometer procedure (Fonteno, 2003). The acrylic column was joined to a 15 cm sealed-base section of polyvinyl chloride (PVC) pipe (i.d. and o.d. equal to the acrylic column) below, and a 30 cm section of PVC pipe above to create a 75 cm packing apparatus. This was loosely filled to the top with substrate and dropped seven times from a height of 17.5 cm to achieve a uniform bulk density (D_b) in the column. The top and bottom PVC sections of the packing apparatus were removed from the column and the substrate surface was leveled across each end of the column before installing the appropriate caps and fittings to be used in the saturated or unsaturated treatments (Fig 1). A fertilizer solution derived from KNO_3 and KH_2PO_4 (Table 2) was prepared for use in both experiments.

Anion transport. Anion transport was evaluated under saturated and unsaturated conditions. Packed columns were fitted with the appropriate PVC fittings for either the saturated or unsaturated treatment (Fig. 1). A circular piece of standard, plastic window screen (diameter = 8.9 cm) was cut to nest within each end-cap at each end of the column to prevent any particles from plugging the outlet and impeding the flow of water. For the saturated treatment, one barbed plastic fitting (3.5 mm i.d.) was centered in each end-cap to create an inlet and an outlet, through which solution could be applied to or drained from the column. At the inlet, the column was attached via 7.9 mm Tygon® PVC tubing to a three-way valve and two glass 10 L Mariotte bottles, one containing deionized (DI) water and the other containing a fertilizer solution. Mariotte bottles allow for water to flow through the column at a constant pressure, which is dictated by the difference in height (z) between the outflow tube at the base of the column and the lower end of the Mariotte bottles' air inlet tube (Δz = 54.45 cm).

Once packed, each rep of the saturated treatment was conducted using the following procedure: (1) Saturation: The column was slowly saturated from below by connecting the lower end of the column to the deionized (DI) water source. Once saturated, water flow was stopped and the column was allowed to rest for one hour. (2) Pore flush: DI water was passed through the column by adjusting the three-way valve to allow water to flow freely from the DI-containing mariotte bottle and through the column. This continued until effluent electrical conductivity (EC) was steady, as indicated by the collection of consecutive 100 mL effluent samples and analysis with an Orion 4-Star benchtop meter equipped with a DuraProbeTM 4-Electrode Conductivity Cell (Thermo Fisher Scientific, Beverly, MA). (3) Tracer application: Without pause, the three-way valve was switched to allow solution to flow freely from the fertilizer-containing mariotte bottle to the column. Effluent was collected in 150 mL increments and each sample collection time was recorded. This continued until three PV (1 PV ≈ 1 L) of effluent were collected to ensure that the majority of any late-arriving solute after 1 PV (relative to the aforementioned piston flow model) was reflected in the BTC. (4) DI application: Without pause, the three-way valve was switched back to allow DI water to again flow from the DI-containing mariotte bottle to the column for the generation of an additional 3 PV of effluent, which was also collected in 150 mL increments with the sample collection times recorded. The rate at which solution moved through the column throughout steps 3 and 4 was determined to be 2.5 $mL \bullet sec^{-1}$ ± 0.1 SE.

After the desired effluent volume had been collected, the column was allowed to drain to container capacity (CC) for one hour, after which the column was weighed, emptied and the substrate placed in an oven to dry at 60 C. This sequence was repeated for each of three replicates using a newly packed column.

In the unsaturated treatment, the number of effluent samples and total effluent volume collected were the same as the saturated treatment. Instead of connecting to mariotte bottles for the application of fertilizer solution and DI water, the lower end of the column was fitted with a false-bottom PVC flat-cap, with 20 evenly distributed, 8 mm holes (Fig. 1). An identically sized piece of mesh screen was nested in this cap to minimize the loss of substrate. The upper end of the column was fitted with a PVC coupler to support a diffuser 5 cm above the substrate surface (Fig. 1). The diffuser was a modified PVC flat-cap which contained 16 evenly distributed, 2 mm holes that facilitated an even distribution of solution over the substrate surface. The tracer solution (step 3) or DI water (step 4) was poured, in 75 mL increments, every 2 minutes into the diffuser. The saturation procedure (step 1) was modified by placing the packed column in a 19 L bucket, which was slowly filled with DI water. As the bucket filled, DI water entered the column through the lower, false-bottom flat-cap until the water level reached the substrate surface, at which point it was allowed to rest for one hour, was then removed and allowed to drain for 15 minutes. Upon finishing step 4, the substrate was allowed to drain to CC and processed in the same manner as the saturated column.

Cation transport. Cation transport was evaluated under saturated conditions and followed the same procedure (steps 1 – 4) used in the saturated treatment of expt. 1, with the following exceptions. In step 2 (pore flush), a HI 9813-6 pH / EC meter (Hanna Instruments, Woonsocket, RI) was used to measure EC and pH. In step 3 (tracer application), two PVs of effluent were collected. The sequence was conducted for three repetitions, using a newly packed column for each treatment. The average rate at which solution moved through the column was determined to be 4.5 $mL \bullet sec^{-1}$ ± 0.9 SE during steps 3 and 4.

Data analysis. Each effluent sample was analyzed for EC. In addition, NO_3^-, PO_4^{3-}, K^+, Mg^{2+} and Ca^{2+} concentrations were measured via an ICS-1600 ion chromatography system (Thermo Fisher Scientific, Madison, WI) equipped with a 4 x 250 mm (i.d. x length) AS22 anion-exchange column, a 4 x 250 mm CS12A cation-exchange column and an AS-AP auto-sampler on a 25 µL sample loop driven by an isocratic pump. The resulting EC readings and ion concentrations were converted to relative concentrations (RC = C/C_o) for the parameter of interest (EC or ion concentration), and are presented as BTCs, along with mean and standard error (SE). Effluent pH was measured at the onset of tracer application (step 3), at the transition between tracer and DI application (between steps 3 & 4) and at the end of DI application (step 4).

The data points were partitioned by the fertilizer (step 3) and DI (step 4) application steps for the saturated and unsaturated treatments of the anion transport expt. and were subject to logistic regression (Eq. [1]),

$$y = \frac{1}{1 + \mathrm{Exp}(-a(x-b))} \quad [1]$$

where a = growth rate and b = inflection point (RC = 0.5). Inflection points and growth rates were subjected to one-way analysis of variance ($\alpha = 0.1$) (Marini, 1999). All data were processed using JMP® Pro version 10.0.2 (SAS Institute Inc., Carey, NC).

RESULTS

Anion transport. Solute transport processes were different between unsaturated and saturated conditions as indicated by the shape of the BTCs (Fig. 3) and their regression model parameters (Table 3). Tracer breakthrough occurred earlier (i.e., with less effluent volume) during unsaturated conditions, for the application of both the tracer solution and DI water (Table 3). During the application of tracer solution (step 3) the inflection point (parameter b), or center of the BTC where RC = 0.5, occurred with 229.3, 235.5 and 209.4 mL less effluent under unsaturated than saturated conditions for the EC, NO_3^- and PO_4^{3-} BTCs, respectively (Table 3). Similarly, when the tracer solution was flushed from the substrate pores (step 4), the inflection point occurred with 197.9, 199.9 and 173.9 mL less effluent under unsaturated conditions for the EC, NO_3^- and PO_4^{3-} BTCs, respectively. Similar effects were seen for the BTC growth rates (parameter a), where the parameter was of greater magnitude for the unsaturated treatment for each tracer during both the tracer and DI application steps (Table 3). However, during the application of DI water, the curves move in the opposite direction (Fig. 3; RC moves from 1 to 0) and subsequently, parameter a is negative. Throughout steps 3 and 4, effluent pH was determined to begin at 6.51 ± 0.08 SE at the onset of tracer application, 5.45 ± 0.04 SE at the transition between tracer and DI application and 6.62 ± 0.06 SE at the end of DI application.

Cation transport. During application of tracers (step 3), the movement of an infiltrating cation (K^+) through the column was retarded, relative to the movement of the anion, NO_3^- (Fig. 2a). Throughout the experiment, a total of 204.8 mg of K^+ was applied to each column. Of that total, 129.1 mg ± 4.0 SE (3.3 meq ± 0.1 SE) was leached, leaving 75.7 mg ± 4.0 SE (1.9 meq ± 0.1 SE), or 37.0% of applied K^+ retained by the substrate. This quantity of retained K^+ represents 1.2% of the available CEC for this substrate. Furthermore, 15.6 mg Ca^{2+} ± 0.6 SE and 7.8 mg Mg^{2+} ± 0.5 SE were leached throughout the experiment. This represented a combined 1.4 meq ± 0.1 SE of Ca^{2+} and Mg^{2+} and accounted for 43.1% of the retained K^+.

DISCUSSION

These findings provide valuable information on the transport of fluids and solutes through a pine-bark medium and their chemical interactions. Solute movement proved to be different under saturated and unsaturated conditions. The movement of water is affected by pore or channel size, and the degree to which they are interconnected (Ma, 1997). Drzal et al. (1999) demonstrated that pine-bark substrates contain many pore sizes that range from macropores (> 416 μ) to ultramicropores (< 0.2 μ). With this in mind, the preferential flow of water through macropores (less restricted) over micropores (more restricted) may lead to a portion of the applied tracer solution reaching the base of the column more quickly via transport through macropores.

Furthermore, within a saturated pore, solution will flow at a higher velocity in the center of the pore than near the particle surfaces where physical and chemical interactions between water and the particle surfaces may restrict flow. Consequently, a range of pore water velocities exist within a pore (driven by the solutions proximity to the particle surface) and within the bulk substrate (driven by the pore or channel size distribution). This range of pore sizes and pore water velocities will allow for a portion of the applied tracer solution to arrive at the opposite end of the column earlier (via travel through the center of pores) than others (slower transport near particulate surfaces), hence complete solute breakthrough (RC changes from 0 to 1 or 1 to 0) is a gradual process.

During unsaturated conditions, a distribution of pore water velocities would still occur as a result of flow through macro and micropores. However, since water flows predominately along particulate surfaces in unsaturated conditions, the development of very fast pore water velocities found in the center of saturated macropores is presumably less prone to develop. Therefore, the range of pore water velocities that occur during unsaturated conditions would be smaller than saturated conditions. This smaller range of pore water velocities may lead to a more even boundary between the applied tracer solution and the old pore water, that allows the transition from RC = 0 to 1 to occur more quickly (over a smaller portion of the Fig. 3 X-axis or effluent volume), a trend that is reflected by the previously discussed early breakthrough observed in the unsaturated treatment of the anion transport expt.

During active, saturated solute transport in the cation expt., the movement of an infiltrating cation (K^+) through the substrate was quite different than the previously discussed movement of anions. This may have contributed to the lower growth rates observed in the EC BTCs as compared to that of NO_3^- and PO_4^{3-} in the anion transport expt. Since EC is a measure of the bulk ions in the solution, the relatively low growth rates of the EC BTC may have been caused by the slower movement of K^+ through the substrate compared to NO_3^- (Fig. 2a).

The chemical interaction between K^+ and pine-bark cation exchange sites reduced the total load of K that was leached from the substrate. During this process, other cations (Ca^{2+} and Mg^{2+}) were displaced from these exchange sites. Fig. 2b shows that the meq of K that was calculated to have been retained by the substrate throughout the experiment, followed a similar trend to the combined meq of Ca^{2+} and Mg^{2+} that was leached. The fact that the magnitude of the Ca^{2+} and Mg^{2+} curve is less than the retained K^+ curve and that leached Ca^{2+} and Mg^{2+} only accounted for 43.1% of retained K^+, suggests that other, unmeasured cations were exchanged by K^+. Pokorny (1979) reported the presence of B, Cu, Fe, Mn and Zn in pine-bark, which may have also interacted with K^+ on bark exchange sites.

Interestingly, the amount of K^+ that was retained, accounted for only 1.2% of the available CEC of the substrate. This finding alone warrants further research into a functional quantification of the cation exchange that occurs under varying conditions (i.e., ion species, resonance times, pH and moisture content) that are likely to occur in a production scenario, such as during fertilizer application or between irrigation events. Daniels and Wright (1988) found surprisingly few differences between the CEC of various pine-bark particle size fractions, and hypothesized that the internal porosity of pine-bark may account for a significant portion of the overall CEC. Mohammadi et al., (2009) discussed an immobile fraction of the soil solution that, when accounted for in prediction models, allowed for a fairly accurate prediction of solute breakthrough. Pokorny (1987) found that the internal porosity of pine-bark accounted for 42.7 to 44.0% of its total volume. Though, the quantity and mobility of the internal pore solution, and the accessibility of internal pores to ions in a solution that is freely flowing through the substrate is in question.

An unexpected observation while conducting both the cation and anion expts. was that during the pre-experiment DI flush (step 1), the effluent was consistently cloudy, and had a light brown color that became clear when fertilizer solution was applied (step 2). It became cloudy again when DI water was re-applied in step 3. A similar effect was observed in previous CEC studies (Daniels and Wright, 1988), where the washing of bark with distilled water after ion displacement produced a cloudy solution. Their observations and ours may suggest an interaction between soluble organic materials and applied fertilizer ions. It is possible that when the substrate pores are comprised mainly of DI water (low ionic strength and high pH), soluble organic materials are drawn away from the bark and into the pore solution. Conversely, when the pore solution is comprised mainly of fertilizer solution (high ionic strength and low pH) the extraction of soluble organic materials is restricted.

CONCLUSION

The behavior of individual ion species, during active solute transport through a pine-bark substrate, differed with the ion species (cation or anion) and the method of analysis (saturated or unsaturated pores). Anions were passed through the substrate relatively unobstructed, where cations were retained by the pine-bark to an extent that constituted a surprisingly small portion of the substrates measured CEC. The findings discussed here provide insight into how individual ions move through and leach from a pine-bark substrate during irrigation events, and how the leached nutrient load may be affected by the volume of water that is drained from the substrate. Several factors appear to be occurring that affect the movement of solutes trough pine-bark substrates, including the dispersion of tracer ions via macropore (relatively unrestricted) and micropore (relatively restricted) flow, diffusion of the tracer ions across the concentration gradients within the substrate, and chemical interaction or exchange between tracers bark particle exchange sites. The approach employed in this study may be used in horticultural research to better understand how nutrients move through and leach from soilless substrates during irrigation. Expanding this knowledge base may lead to the refinement of crop models and production practices that improve nutrient and water use efficiency in container nurseries.

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TABLES

Table 1. Physical properties of a substrate comprised of 9 pine-bark : 1 sand (% by vol.) used in the cation and anion transport expts.

Experiment	Bulk density ($g \bullet cc^{-1}$)	Total porosity	Air space	Container capacity
		------------------------- (% by vol.)	---------------------------	
		Porometer analysis		
Anion	0.326	72.5	26.5	46.0
Cation	0.288	81.5	31.0	50.5
		Measured in saturated columns		
Cation	0.324	77.5	29.4	48.1
		Measured in unsaturated columns		
Cation	0.324	----	----	50.2

Table 2. Fertilizer solution electrical conductivity (EC) and ion concentration used in the cation and anion transport expts. Fertilizer ions were derived from KNO_3 and KH_2PO_4.

	EC	NO_3	PO_4	K
Experiment	(µS/cm)	----------------------	(mg/L)	---------------------
Anion	345.2	95.4	118.0	106.1
Cation	333.0	106.0	105.1	105.0

Table 3. Parameter estimates for the anion transport expt. breakthrough curves (BTCs) developed by applying a tracer solution (derived from KNO_3 and KH_2PO_4) and deionized (DI) water to a 9 pine-bark : 1 sand (% by vol.) filled column under saturated and unsaturated conditions.

		Tracer application			DI water application		
Tracer	Condition	a[z]	b	R^2	a	b	R^2
EC	Sat.	0.0027	970.6	0.93	-0.0038	4002.4	0.98
	Unsat.	0.0038	741.3	0.92	-0.0054	3804.5	0.98
	p-value	0.0062	0.0008	---	0.0030	0.0116	---
NO_3^-	Sat.	0.0044	918.6	0.97	-0.0045	4007.2	0.98
	Unsat.	0.0060	683.1	0.99	-0.0069	3807.3	0.99
	p-value	0.0209	0.0104	---	0.0011	0.0139	---
PO_4^{3-}	Sat.	0.0042	890.4	0.96	-0.0042	3986.7	0.98
	Unsat.	0.0054	681.0	0.99	-0.0061	3812.8	0.99
	p-value	0.0317	0.0216	---	0.0040	0.0241	---

[z]EC, NO_3^- and PO_4^{3-} tracer data were fit with the logistic regression model $y = 1/\{1 + Exp[-a(x-b)]\}$, where y is the relative tracer concentration ($RC = C/C_o$, where C = effluent concentration and C_o = initial concentration), x is the cumulative effluent volume, a is the growth rate and b is the inflection point (value of x when RC = 0.5).

FIGURES

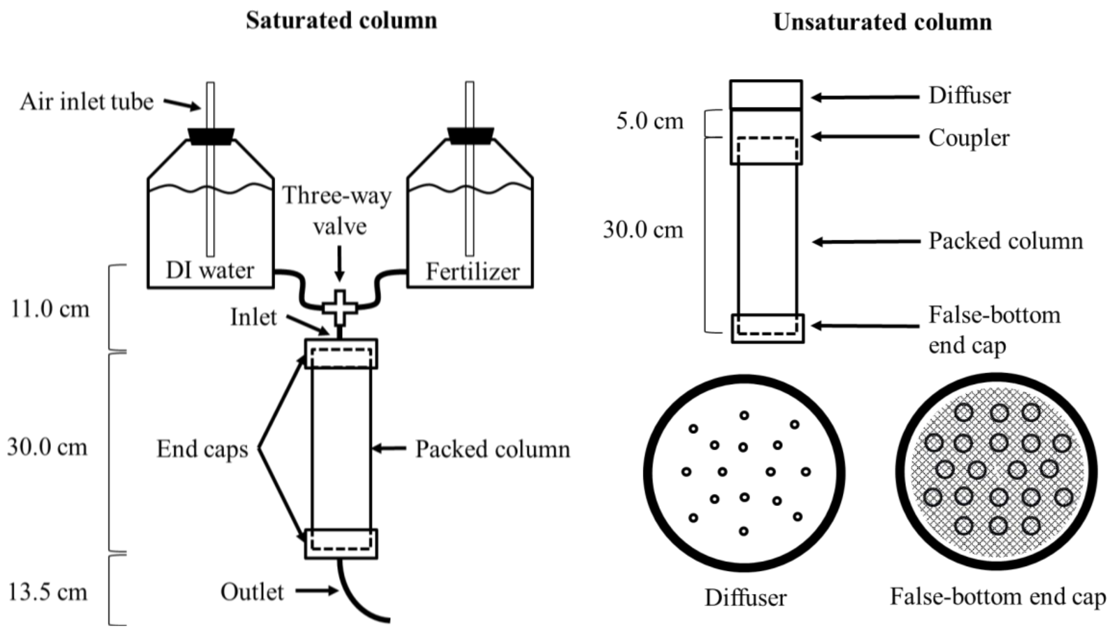

Fig. 1. Physical setup of the saturated and unsaturated column expts. for measuring ion transport in pine-bark substrates.

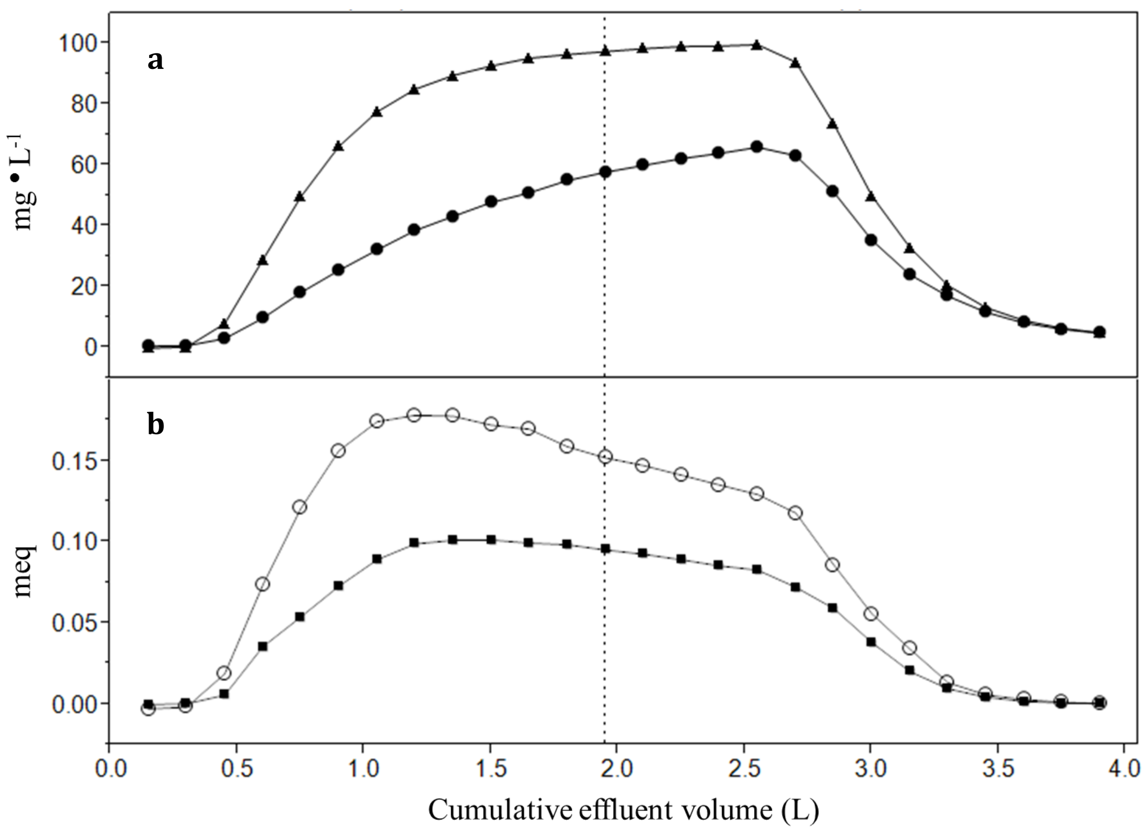

Fig. 2. Cation transport expt. results showing a) ion release curves for (▲) NO_3^- and (●) K^+ effluent concentration, and b) exchanged cations (■) ∑ Ca^{2+}, Mg^{2+} equivalent charge (meq) in effluent and (○) approx. meq K^+ retained = meq NO_3^- – meq K^+. The vertical dashed line represents the point at which the input solution was switched from fertilizer to deionized water.

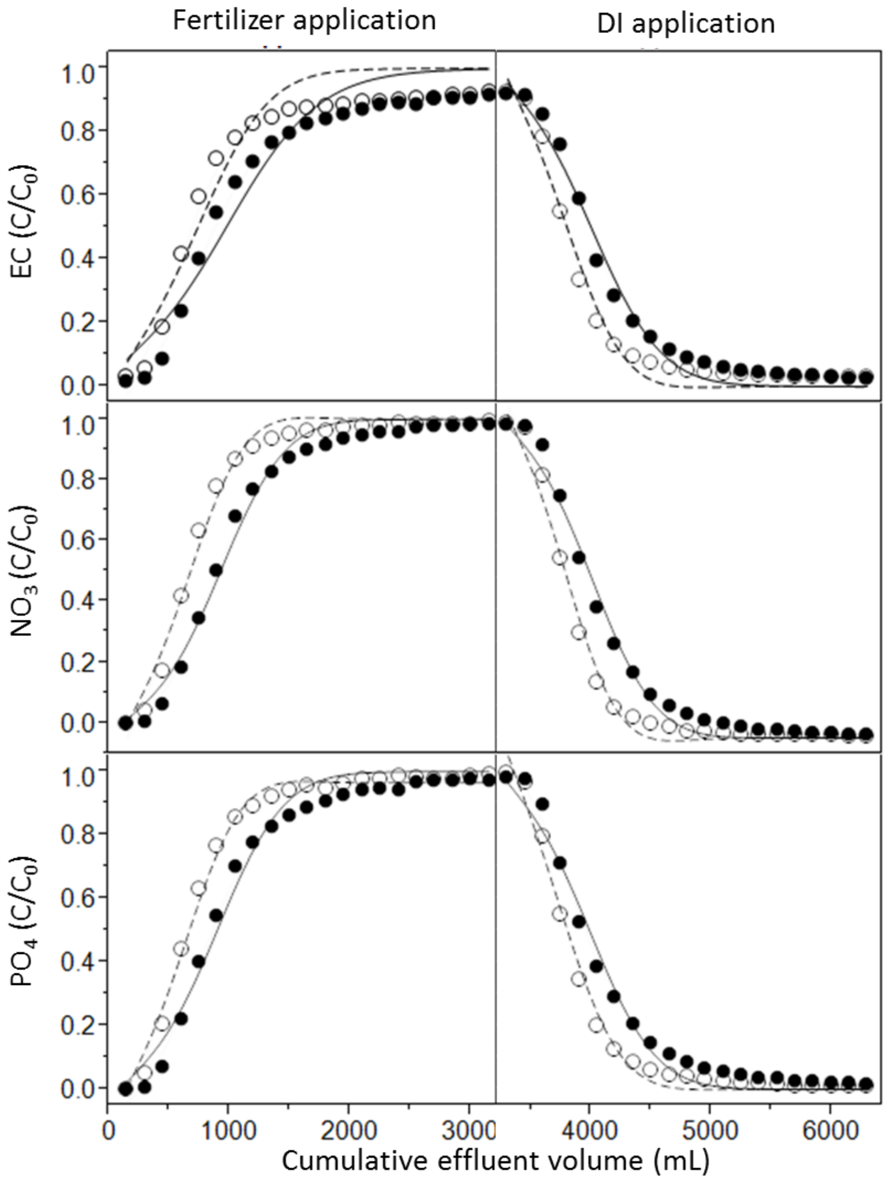

Fig. 3. Anion transport expt. breakthrough curves showing electrical conductivity (EC), nitrate (NO_3^-) and phosphate (PO_4^{3-}) relative effluent concentration (C/C_o; where C and C_o = effluent and input solution concentration, respectively) during the application of a fertilizer solution (≈ 100 mg • L^{-1} NO_3^- & PO_4^{3-} each) and deionized (DI) water to a pine-bark substrate under (●) saturated and (○)

unsaturated conditions. The vertical line indicates when the input solution changed from fertilizer to DI water. Parameters for the (---) unsaturated and (━) saturated regression lines are reported in Table 3.

Chapter 4

Controlled-release fertilizer placement affects the leaching pattern of nutrients from nursery containers during irrigation

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Controlled-release fertilizer placement affects the leaching pattern of nutrients from nursery containers during irrigation

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Controlled-release fertilizer placement affects the leaching pattern of nutrients from nursery containers during irrigation

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Abstract. Maximizing nutrient use efficiency while minimizing nutrient leaching and non-point source contributions from containerized crop production systems are goals of researchers and growers. These goals have led to irrigation and crop nutrition management practices that reduce fertilizer and irrigation expenditures and reduce the nutrient load into the environment. However, one area that has received little attention, and may lead to the further refinement of crop management practices, is how dissolved nutrients (solutes) move through a substrate while water is being applied during irrigation. A study was conducted to characterize the effect of controlled-release fertilizer (CRF) placement method on changes in leachate nutrient concentration throughout an irrigation event and to evaluate these changes at different times throughout a production season. A 9 bark : 1 sand (% by volume) substrate was placed in 2.7 L nursery containers (fallow) and was treated with topdressed, incorporated and dibbled CRF, or did not receive CRF. The nutrient leaching pattern was evaluated at 3, 9 and 15 weeks after potting (WAP). Leachate nutrient concentration was the highest in the first 50 mL of effluent and steadily diminished as irrigation continued for the topdressed, incorporated and the no CRF treatments. Effluent nutrient concentration from containers with dibbled CRF generally increased

throughout the first 150 mL of effluent before plateauing briefly and then diminishing. The nutrient load that leached with higher volumes of irrigation water was similar between incorporated and dibbled CRF placements. However, the unique nutrient leaching pattern of the dibbled CRF placement method allowed for a lower effluent nutrient load when LFs are low. Dibble may be an advantageous CRF placement method that allows for the conservation of expensive fertilizer resources and mitigates non-point source nutrient contributions by reducing undesired nutrient leaching during irrigation.

INTRODUCTION

Maximizing nutrient use efficiency and minimizing leaching and non-point source contributions via runoff are persistent challenges in containerized crop production that drive both researchers and growers to develop new technologies and methods to manage crop nutrition. Controlled-release fertilizers (CRFs) are a recommended (Bilderback et al., 2013) and widely adopted (Dennis et al., 2010) nutrient delivery method for containerized crops. Controlled-release fertilizers contain encapsulated, solid mineral nutrients that, in the presence of water, are slowly dissolved and released to the surrounding substrate solution over an extended period of time; dissolution and release are dictated by factors such as coating technology (Adams et al., 2013) and temperature (Adams et al., 2013; Husby et al., 2003).

The performance of CRFs throughout a typical production season has been extensively studied (Alam et al., 2009; Broschat and Moore, 2007; Cabrera, 1997; Colangelo and Brand, 2001) and their use has been demonstrated to be an effective fertilizer application method in reducing N and P runoff as compared to systems where dissolved nutrients are applied via irrigation water (i.e., fertigation or liquid feed) (Wilson and Albano, 2011). However, the movement of dissolved nutrients (solutes) released from CRFs through a soilless substrate during the application of water (i.e., during irrigation) has received little attention in the current body of literature. Hoskins (2014) found that the movement of applied irrigation water through pine-bark based substrates is not uniform, due to the formation of channels that form in dry regions of the substrate profile. However, how this uneven movement of applied irrigation water affects the leaching of mineral nutrients from the substrate is not as well understood. Hoskins (2014) also conducted solute transport experiments using pine-bark filled columns and demonstrated that the anion fertilizer species nitrate (NO_3^-) and phosphate (PO_4^{3-}) moved through the substrate very quickly as compared to the cation potassium (K^+).

Research has shown that reducing the volume of effluent generated during irrigation, measured by practitioners as a leaching fraction (LF = volume leached ÷ volume applied), results in less total nutrients leached (Owen et al., 2008; Tyler et al., 1996). Furthermore, Niemiera and Leda (1993) found similar results with regard to total nutrient load leached, but also reported that NO_3^- and NH_4^+ concentrations in the substrate solution, as indicated by a pour through (PT) procedure, were higher at reduced LFs. Collectively, these findings suggest that before irrigation, an initially high, CRF-derived nutrient concentration resides in the pore-water solution and is flushed out to an extent that is dependent on the volume of water leached. However, the mechanisms behind this nutrient leaching and leachate volume relationship, and how solutes move from the substrate solution and leave a container during irrigation are not understood. Current knowledge on solute transport is based on work in mineral soils or sands, where physical and chemical properties can be quite different than bark-based soilless substrates.

There are two key attributes of CRFs that are important in understanding the principles of solute transport during irrigation. First is the seasonal variability in the rate of nutrient release, which is higher in the early portion of a CRFs life (Merhaut et al., 2006). Furthermore, the nutrient release rate is affected by choice of CRF placement in the container. For example, the maximum release rate occurs later in the season for the topdressed method (i.e., surface applied) than for the incorporated method (i.e., distributed throughout soilless substrate) (Alam et al., 2009). Due to the inherent seasonal variability in CRF nutrient release rates, we hypothesize that solute transport dynamics also change. The second attribute to consider is the non-uniform nutrient distribution throughout a substrate. This distribution would be affected by CRF placement (topdressed, incorporated or dibbled), type (liquid vs. solid) and irrigation management. Brown and Pokorny (1977) demonstrated the variability in potassium distribution throughout a substrate profile when applied in soluble form to the substrate surface. Altland et al. (2004) and Broschat and Moore (2003) evaluated the effect of fertilizer placement on crop quality and weed growth in containers. They found a species-specific response in crop growth to the placement of CRFs and a decrease in weed growth when dibbled (i.e., all fertilizer placed directly in the center of the substrate). As a whole, these studies suggest that nutrient availability and distribution is variable throughout a substrate profile and is affected by CRF placement.

Developing a detailed understanding of how factors such as the length of time that CRF prills have been in production and their placement method affect the pattern which individual nutrients leach during irrigation will lead to a better understanding of nutrient load leached during a single irrigation event. A study was conducted with the objectives of 1) characterizing the changes in leachate nutrient concentration throughout an irrigation event using the manufacturers' recommended CRF application rate (Expt. 1) and matched N rates (Expt. 2) for given CRF placement methods, 2) evaluating the variability in leachate nutrient concentration changes (objective 1) at different times in a production season, and 3) relating the within-irrigation changes in leachate nutrient concentration changes to cumulative nutrient load leached with increasing leachate volumes. This information was used to make inferences about solute transport in pine-bark substrates during irrigation. We hypothesize that nutrient distribution throughout a substrate profile is affected by the placement of CRF in the container and that this distribution affects the pattern, which nutrients are leached from the container during individual irrigation events. The results may be used by researchers to improve nutrient models, such as that developed by (Majsztrik, 2011), and recommendations for fertilizer and irrigation management in container nurseries.

MATERIALS AND METHODS

On 21 June 2013, a 9 bark : 1 sand (by volume) substrate was amended with 1.8 kg•m^{-3} (3 lb•yd^{-3}) crushed dolomitic lime (Rockydale Quarries Corp., Roanoke, VA) and an equal quantity of pelletized dolomitic lime (Kelly's Limestone LLC., Kirksville, MO) and was placed into trade gallon (2.7 L) nursery containers (Myers industries, Middlefield, OH). Porometers were used to determine the substrate's static physical properties resulting in the following observed properties: total porosity = 78.7 % vol.; container capacity = 52.3 % vol.; air space = 26.4 % vol.; bulk density = 0.325 g•cm^{-3}. Particle size distribution (percent by weight), as determined by a 5-minute mechanical agitation with oven-dried substrate, was as follows: > 6.3 mm = 8.0; 6.3 to 2 mm = 27.6; 2 to 0.71 mm = 37.9; < 0.71 mm = 26.5.

Expt. 1. A pre-weighed quantity of 16N–2.6P–9.1K (16N–6P_2O_5–11K_2O with 7.2% N–NO_3, 8.8% N–NH_4 with micronutrients; 5-6 month or 20-24 week CRF; Harrell's, Lakeland, FL) was applied at the manufacturers recommended rate of 11.0, 15.9, 15.9 and 0.0 g per container for topdressed, incorporated, dibble and a control (no CRF) placement methods, respectively. Topdressed CRF was distributed evenly over the substrate surface. Incorporated CRF was pre-mixed into the substrate on an individual container basis. Dibbled CRF was placed in a 3 inch deep, hand-formed hole in the substrate surface that was backfilled after CRF placement. All treatments were fallow (i.e., not containing a plant).

To approximate the percentage of original fertilizer remaining in the CRF at the time of data collection, an extra container was used for each treatment where the CRF was enclosed in a packet made from standard mesh window screen. These packets were collected throughout the duration of the study and their CRF was analyzed to determine the quantity nutrients remaining (Table 1). Topdressed packets were placed in a single circular pouch that covered the entire substrate surface. Incorporated packets were partitioned into three circular pouches that were placed at 1, 3 and 5 inches from the container base. Dibbled packets were enclosed in a small square pouch and was placed in the middle of the vertical and horizontal container profile.

All containers were placed in an open-air research nursery at the Hampton Roads Agricultural Research and Extension Center in Virginia Beach, VA (Lat. 36.892088; Long. -76.179500) where they received a daily, 15-min overhead irrigation (12.7 $mm•hr^{-1}$). Data were collected at 3, 9 and 15 weeks after potting (WAP). At each WAP, containers were brought into the laboratory prior to data collection and weighed repeatedly until reaching an average volumetric water content (VWC) of 37.1% ± 0.4 SE (n = 36) to simulate the field conditions in which water would be applied. Data collection began once the target VWC had been reached. Each container was nested into a custom irrigation platform (Fig. 1), where it was irrigated with deionized (DI) water through a diffuser mounted 27 cm (10.6 in) above the substrate surface. Irrigation was applied at a rate of 300 $ml•min^{-1}$, which is comparable to a 19 $L•hr^{-1}$ spray stake but inherently faster that most overhead irrigation systems. During irrigation, effluent (leachate) from every container was collected and fractioned in the following increments, in sequence: 3 x 50 mL (total = 150 mL), 3 x 100 mL (total = 300 mL), 3 x 200 mL (total = 600 mL) and 3 x 400 mL (total = 1200 mL). This produced a total of 12 samples totaling 2.25 L of effluent. Using the time which leaching was first observed (56 s ± 2 SE, n = 36) and the irrigation application rate, the volume of water applied at each cumulative effluent volume can be calculated and used to approximate the LF (Eq. [1]) at each effluent volume.

$$\mathrm{LF} = \frac{\text{cumulative effluent vol. (mL)}}{5 \times \text{leaching time (s)} + \text{cumulative effluent vol. (mL)}} \qquad [1]$$

Irrigation ended once the effluent for all samples had been collected. Hoskins (2014) found that water moves as a relatively even front through pine-bark in fallow nursery containers when the moisture distribution is even throughout the container profile. Therefore, the effect of channeling (downward movement of water through specific flow paths) is thought to be minimal in this study. Following irrigation, each container was allowed to drain for one hour, at which point the substrate moisture content was at container capacity (CC). All effluent was collected during this period of post-irrigation drainage and analyzed in the same manner as other effluent samples to determine the post-irrigation nutrient load in drainage water.

An aliquot of each effluent sample was analyzed for electrical conductivity (EC; µS/cm) and pH using an Orion 4-Star benchtop meter equipped with a DuraProbeTM 4-Electrode Conductivity Cell (Thermo Fisher Scientific, Beverly, MA). Nitrate (NO_3), NH_4, PO_4, SO_4, K, Mg and Ca concentrations of effluent were determined using a separate, filtered (0.2 µm) aliquot via an ICS-1600 ion chromatography system (Thermo Scientific, Madison, WI) equipped with a 4 x 250 mm (i.d. x length) AS22 anion-exchange column, a 4 x 250 mm CS12A cation-exchange column and an AS-AP auto-sampler on a 25 µL sample loop driven by an isocratic pump.

The experiment was a 4 (CRF placement) x 3 (WAP) factorial, using a completely randomized design with three replicates per treatment level, resulting in 36 total containers used in the study (not counting the containers with CRF packets). Separate sets of 12 experimental units (containers) were used for each WAP. The relationship between EC and individual leachate nutrient concentrations were evaluated using Pearson’s correlation coefficient and linear regression. Slopes and intercepts of these regression lines were pooled, blocked by CRF placement method. Data were subjected to analysis of variance ($\alpha = 0.1$) (Marini, 1999) and means separation by way of Tukey's HSD when appropriate. All data were processed using JMP® Pro version 10.0.2 (SAS Institute Inc., Carey, NC).

Expt. 2. On 15 Aug. 2013, a similar co-experiment was initiated using equal N rates (15.9 g of the same CRF used in experiment 1) for both topdressed and incorporated CRF placement methods to ensure that the same nutrient leaching patterns hold true when the quantity of CRF applied to topdressed containers is equal to that of incorporated CRF. All materials and management practices were in this experiment were the same as expt. 1 except for the different CRF application rate. Treatments included only topdressed and incorporated CRF placements and data collection only occurred at one time in the season (6 WAP). The experiment was a completely randomized with two levels of CRF placement (topdressed and incorporated) and three replicates per treatment level (n = 6). Data collection procedures and analysis methods were identical to expt. 1.

RESULTS AND DISCUSSION

Analysis of the EC values, nutrient concentrations and nutrient load at each effluent collection volume indicate an interaction between CRF placement method and WAP. Therefore, the simple effects (i.e., the effect of one treatment within only one level of the other treatment) of CRF placement and WAP will be discussed.

Nutrient leaching pattern. Fertilizer placement affected the pattern in which nutrients leach (changes in effluent concentration with effluent volume) from the base of a container during irrigation. In expt. 1, effluent EC (Fig. 2) was the highest in the first 50 mL of effluent and steadily diminished as irrigation continued for topdressed, incorporated and the control (no CRF). However, the pattern was quite different for dibbled CRF placements and was much more variable. Effluent EC from containers with dibbled CRF increased for the first 150 mL of leachate, plateaued briefly and then diminished as irrigation continued. The expt. 1 leaching pattern of N-NO_3 and P-PO_4 (Fig. 2) followed these same general trends as EC with increasing effluent volumes and was affected by CRF placement similarly. Nitrate release curves (RCs) took a more similar shape to the EC RCs than P-PO_4. In expt. 1, N-NO_3 was the predominant ion present in leachate (reflective of the CRF formulation), and is likely responsible for most of the EC. Overall, each ion exhibited a strong linear correlation with EC (Table 2). Comparison of the mean slopes from each linear regression line allows the authors to infer individual ion contribution to the bulk EC ($P < 0.0001$) is as follows: NO_3 > SO_4, K > Mg, Ca, PO_4 and NH_4. These results suggest that effluent EC may serve as a strong indicator of effluent NO_3 concentration and a moderate indicator of SO_4 and K.

The general pattern of nutrient leaching with increased effluent volumes from topdressed CRF generally followed the same trend as incorporated CRF, though there was a reduced nutrient load (Table 3) for each ion as leachate volume increased. The same general trend (nutrient load vs. effluent volume) was observed in expt. 2 (Fig. 3), revealing that matched fertilizer application rates (same amount of CRF in both the topdressed and incorporated application methods) produced similar leaching patterns for topdressed and incorporated CRF. The nutrient load leached from containers topdressed with CRF was lower than that for the incorporated treatment. This illustrates the inherent differences in the solute transport mechanisms when CRF is concentrated on the substrate surface (topdressed) rather than dispersed throughout the substrate profile. Nutrient movement from inside the encapsulating membrane to the surrounding substrate environment requires water (Adams et al., 2013), and the reduced moisture content (MC) observed by Hoskins (2014) in the upper portion of the substrate profile likely reduced the capacity for nutrient release as compared to incorporated CRF where individual prills are subject to higher MCs.

Nutrient load in effluent. In expt. 1, the initial amounts of N-NH_4, N-NO_3, P-PO_4, and K in effluent collected (50 mL) from incorporated CRF at 3 WAP, were highest (Table 3) as compared to that of the other CRF placement methods. However, later in the production season (9 and 15 WAP) there were very few differences in ion concentrations between CRF placement methods for the first 50 mL of effluent. The observation that the incorporated CRF placement produced the highest nutrient load in the first 50 mL of effluent is most likely a result of the close proximity of some CRF prills to the base of the container. Similarly, in containers with dibbled CRF, the observation the effluent nutrient concentration peaks after 150 mL effluent had been collected (Fig. 2) is likely a result of the prills being located farther from the base of the container compared to incorporated prills. However, at 350 and 2250 mL cumulative effluent volume (≈ 0.5 and 0.9 LF) (Table 3) there were few differences in nutrient load between incorporated and dibble CRF placement methods. This suggests that with these placement methods, the CRF prills are exposed to similar moisture and temperature conditions, and subsequently release a similar quantity of nutrients into the substrate solution. However, a benefit of dibbled CRF is revealed, in that when effluent volumes are low (0.15 LF), the potential for nutrient leaching is reduced despite a similar quantity of nutrient in the pore solution. This is consistent with the findings of Alam et al., (2009) who found improved growth of container-grown forsythia and less NO_3 in leachate with dibbled CRF and a low LF as compared to other placement methods and LFs.

The 2250 mL cumulative effluent volume can be considered a near maximal flush of all ions in the pore water solution, and therefore represents the quantity of displaceable, non-bound ions in the substrate. Incorporated and dibbled CRF released a similar quantity of displaceable ions into the substrate solution at 3 and 15 WAP (Table 3). Topdressed CRF released less leachable ions than incorporated or dibbled CRF, and was the same as the no CRF treatment at 3 and 15 WAP. This illustrates a difference in the potential quantity of nutrients that may be released from CRF prills in the extreme moisture conditions (i.e., relatively wet during irrigation and dry between) of the substrate surface. Effluent volumes this high are not likely to occur when using recommended irrigation practices. However, quantifying the nutrient load that may be leached with high volumes of water is an important measurement because as Colangelo and Brand (2001) demonstrated, the often high precipitation amounts occurring throughout the production season in the eastern U.S. may induce significant amounts of leaching. Furthermore, Colangelo and Brand (2001) found that precipitation nullified the benefits of high efficiency (micro-irrigation) irrigation systems and LFs in terms of NO_3 load leached over two production seasons, as compared to overhead irrigation and high LFs.

Post-irrigation drainage. The volume of post-irrigation drainage (Table 4) from expt. 1 increased with WAP ($P = 0.0003$). This may be explained by the observation that irrigation water tended to pond on the substrate surface for a few containers at 9 WAT and to a greater extent at 15 WAT. Shrinkage induced by the decomposition and compaction of bark based substrates with time (Altland et al., 2011), and associated reduction in hydraulic conductivity (Nash and Laiche, 1981), may explain the increased frequency at which ponding was observed. After ponding was observed at 9 WAP, shrinkage measurements (i.e., height of substrate in the container) were taken on the remaining containers to be used at 15 WAP. Shrinkage did occur ($P < 0.0001$), and the substrate surface fell by 7.0 mm ± 0.6 SE (n = 12) between 9 and 15 WAP. Dibble and incorporated CRF placements produced the highest $N\text{-}NO_3$ load in the post-irrigation drainage, followed by topdressed CRF (Table 4). Following trends observed in Fig. 2, the N-NO_3 load was highest at 15 WAP. Load values of N-NH_4, P-PO_4 and K (data not shown) follow the same general trends.

Weeks after potting. In expt. 1, from 3 to 9 to 15 WAP, the predominate trend at 50, 350 and 2250 mL cumulative effluent volumes was for the total nutrient load to increase (Table 3). An exception to this trend was the N-NO_3 load leached when CRF was incorporated, in which the load tended to be highest at 15 WAP and least at 9 WAP. Potassium load in the control treatment was highest at 3 WAP for each of the 50, 350 and 2250 mL effluent volumes (Table 4), and is likely a result of inherent amount of soluble K in pine-bark (Raviv and Lieth, 2008) that was eventually leached from the bark with successive irrigations early in the production season. Even though the magnitude of the release curves in Fig. 2, and subsequent nutrient load, for each CRF placement method changed between 3, 9 and 15 WAP, the pattern in which fertilizer salts moved through and leached from the substrate were similar for each placement method and is most likely a result of the aforementioned differences in nutrient distribution throughout the substrate profile.

CONCLUSION

The concentration of ions in container effluent changed throughout the irrigation event and were affected by the CRF application method. Incorporated and topdressed CRF produced their highest effluent nutrient concentrations in the first 50 mL volume of effluent collected before steadily diminishing with increasing effluent volume. Dibbled CRF peaked after approximately 150 mL of effluent had been collected, resulting in a variable load of leached nutrients based on CRF placement and leachate volume.

Incorporated and dibbled CRF placement methods have the potential to produce the greatest quantity of leachable nutrients as compared to the topdressed method. However, a benefit of the dibbled over the incorporated method, is that it less of the leachable nutrients may leave the container when effluent volumes are kept low (low LF), leaving more residual nutrients in the substrate that are available for plant growth. This suggest that the dibble method may be a viable CRF placement method in terms of reducing nutrient leaching and the subsequent environmental impact in situations where growers are able to maintain a low LF, excluding the effect of rainfall. Additionally, the effect of fertilizer placement and effluent volume can be incorporated into models that predict nutrient leaching. Further research is warranted to determine the optimal method for adapting this placement method to containerized crop production systems.

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TABLES

Table 1. Observed, non-replicated, percent of ions remaining in an approx. 20-24 wk. longevity controlled-release fertilizer at 3, 9 and 15 weeks after potting (WAP) by fertilizer placement method (Expt. 1) in a 9 bark : 1 sand (% by vol.) substrate.

	WAP			
Placement	3	9	15	R^2
		N-NO₃		
Topdress	87.7	70.6	54.1	1.00
Incorporated	88.9	42.9	23.4	0.95
Dibble	86.6	42.2	20.9	0.96
		N-NH₄		
Topdress	87.2	76.8	63.5	0.99
Incorporated	92.5	58.2	34.3	0.99
Dibble	93.6	56.7	34.5	0.98
		P-PO₄		
Topdress	81.9	84.4	82.9	0.25
Incorporated	90.5	72.3	57.8	0.99
Dibble	94.2	73.9	49.2	1.00
		K		
Topdress	90.1	85.0	75.6	0.97
Incorporated	93.6	64.4	43.1	0.99
Dibble	91.9	65.0	42.5	1.00

Table 2. Pearson's correlation coeffecinet (α = 0.05) and linear regression parameters describing the relationship between between leachate electrical conductivity and individual ion concentrations during the irrigation (300 mL•min^{-1} with deionized water) of fallow, 2.7 L nursery containers with 9 bark : 1 sand (% by vol.) substrate while blocking for controlled-release fertilizer placement (Expt. 1).

Ion	r	Slope	Y-intercept	R^2
NO_3	0.99	0.29 a^z	-5.87 c	0.99
SO_4	0.99	0.11 b	-2.76 bc	0.99
K	0.99	0.10 b	3.71 a	0.98
Mg	0.98	0.03 c	-2.06 abc	0.97
Ca	0.99	0.03 c	-2.07 abc	0.99
PO_4	0.96	0.03 c	1.94 ab	0.93
NH_4	0.90	0.03 c	1.90 ab	0.81

^{z} Means within column not sharing the same letter are significantly different according to Tukey's HSD ($P < 0.1$).

Table 3. Expt. 1 nurtient load (mg) in container effluent as a function of the cumulative effluent volume (mL) generated during the irrigation of a 2.7 L nursery container and a 9 bark : 1 sand (% by vol.) substrate as affected by controlled-release fertilizer (CRF; approx. 22-wk longevity) placemeent at 3, 9 and 15 weeks after potting (WAP).

	50 mL (0.15 LF[z])			350 mL (0.5 LF)			2250 mL (0.9 LF)		
CRF placement	3	9	15	3	9	15	3	9	15
					N-NH₄				
No CRF	0.0 b[y]	0.0 b	0.0 c	0.0 c	0.0 c	0.0 b	0.0 b	0.0 c	0.0
Dibble	0.0 b B	0.6 a A	0.4 b A	1.3 ab B	7.0 a A	3.8 a AB	7.0 a	29.5 a	37.9
Incorporated	0.5 a	0.7 a	0.8 ab	2.3 a B	5.0 ab A	5.0 a A	5.3 a B	16.4 b AB	20.4 A
Topdress	0.0 b B	0.3 ab B	0.9 a A	0.2 bc B	4.0 b A	4.7 a A	0.4 b B	12.6 b A	14.2 A
					N-NO₃				
No CRF	0.0 c B	0.0 b B	0.0 b A	0.0 c B	0.0 b B	0.1 c A	0.0 b B	0.0 b B	0.2 c A
Dibble	0.5 b B	1.2 a AB	1.6 ab A	9.8 ab	11.3 a	12.4 b	37.3 a	39.3 a	57.8 ab
Incorporated	2.1 a AB	0.9 ab B	3.1 a A	12.5 a B	6.8 a C	18.5 a A	28.6 a B	23.0 a B	68.9 a A
Topdress	0.4 bc B	1.7 a AB	2.7 a A	2.9 bc C	10.0 a B	15.6 ab A	8.6 b C	26.2 a B	45.5 b A
					P-PO₄				
No CRF	0.1 b A	0.0 b B	0.0 c B	0.6 A	0.0 c B	0.0 c B	1.5 A	0.0 c B	0.1 c B
Dibble	0.0 b C	0.1 ab B	0.2 b A	0.9 B	2.0 a A	2.1 b AB	2.9	10.7 a	17.1 a
Incorporated	0.2 a B	0.2 ab B	0.5 a A	1.3 B	1.6 b B	3.1 a A	3.5 B	5.6 b B	13.6 ab A
Topdress	0.1 b B	0.3 a AB	0.4 ab A	0.5 B	1.6 b A	2.3 ab A	1.4 C	4.4 b B	7.4 bc A
					K				
No CRF	1.6 b A	0.3 B	0.3 b B	9.3 b A	2.0 b B	2.2 b B	27.8 b A	5.3 c B	7.3 b B
Dibble	1.8 b AB	0.9 B	2.6 ab A	16.1 ab	16.6 a	20.5 ab	57.7 a	55.5 a	118.4 a
Incorporated	3.7 a A	1.3 B	3.9 a A	22.5 a AB	9.3 a B	28.5 a A	61.0 a B	32.3 b B	133.3 a A
Topdress	1.9 b	1.9	3.5 a	11.6 b	11.0 a	21.1 ab	38.4 ab	29.9 b	62.6 ab

[z]Leaching fractions (LF) are approximated based on the average time which leaching began (56 s ± 2 SE, n = 36), irrigation application rate (300 mL•min^{-1}) and the volume of effluent collected, not measured irrigation volumes.

[y]Means not sharing the same lower-case letter within columns or upper-case letters within row (delimited to 50, 350 or 2250 mL effluent groups) are significantly different according to Tukey's HSD ($P < 0.1$). The absence of letters indicates no significant difference.

Table 4. Expt. 1 N-NO_3 load (mg) in post-irrigation drainage after the irrigation (300 mL•min^{-1} with deionized water) of fallow, 2.7 L nursery containers with a 9 bark : 1 sand (% by vol.) substrate as affected by controlled-release fertilizer (CRF) placement at 3, 9, and 15 weeks after potting (WAP).

	WAP					
Placement	3		9		15	
No CRF	0.0 b[z]		0.0 c		0.0 b	
Dibble	1.7 a	A	2.4 a	A	6.8 a	B
Incorporated	0.9 ab	A	1.5 ab	A	5.6 a	B
Topdress	0.3 b	A	1.0 bc	AB	4.1 ab	B
Volume (mL)	282.2	A	320.8	A	385.0	B

[z] Means not sharing the same lower-case letter within columns or upper-case letters within row (delimited to 50, 350 or 2250 mL effluent groups) are significantly different according to Tukey's HSD (P < 0.1). The absence of letters indicates no significant difference.

FIGURES

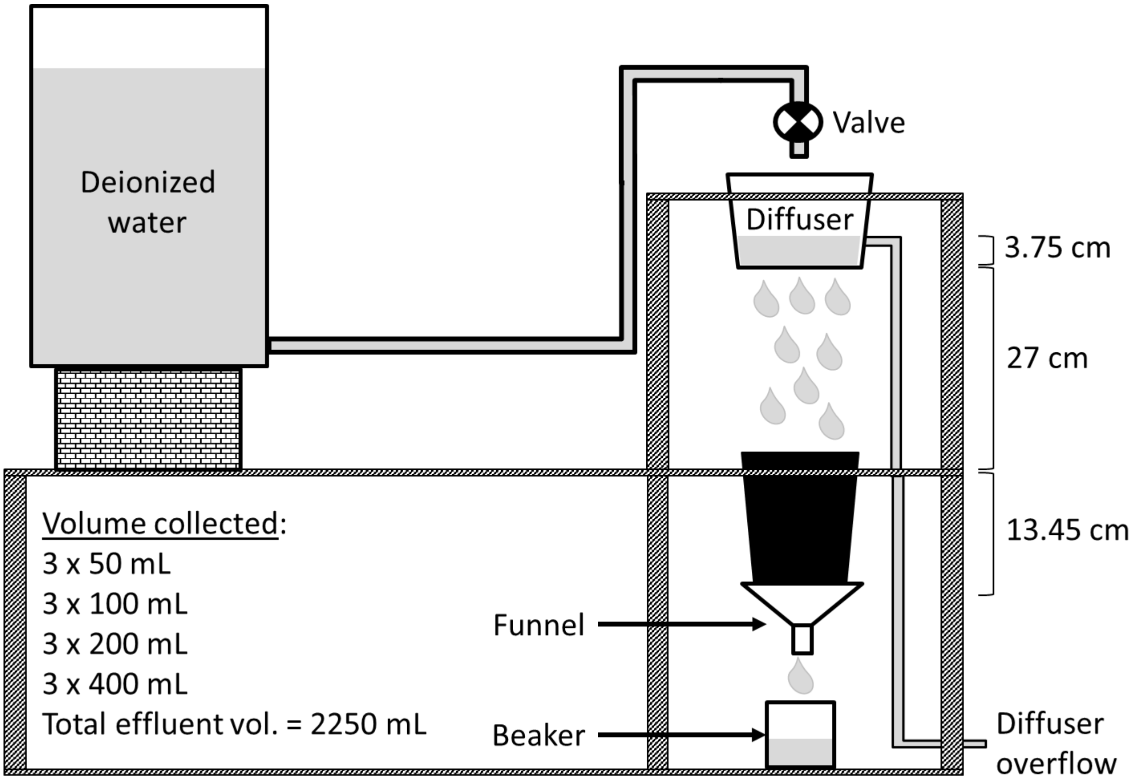

Fig. 1. Physical setup of the irrigation platform depicting the application of deionized irrigation water through a diffuser with constant head and the collection of effluent throughout the irrigation event.

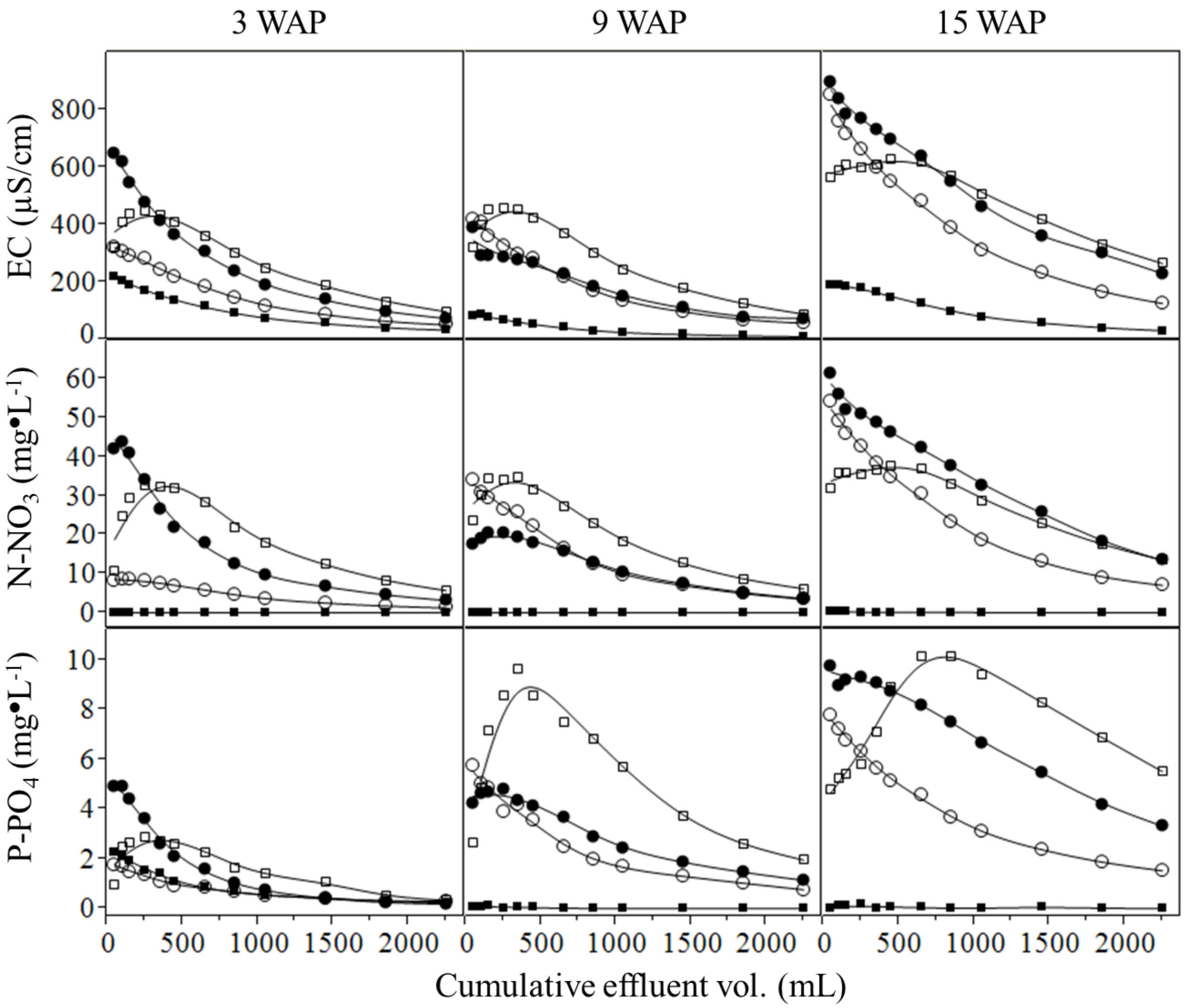

Fig. 2. Expt. 1 release curves showing changes in effluent electrical conductivity (EC), nitrogen ($N\text{-}NO_3$) and phosphorus ($P\text{-}PO_4$) concentration as a function of cumulative effluent volume at 3, 9, and 15 weeks after potting (WAP). Fallow, 2.7 L nursery containers with a 9 bark : 1 sand (% by vol.) substrate and controlled-release fertilizer applied as (□) dibble, (●) incorporated, (○) topdressed or (■) without CRF during irrigated with deionized water (DI) at a rate of 300 mL•min^{-1}.

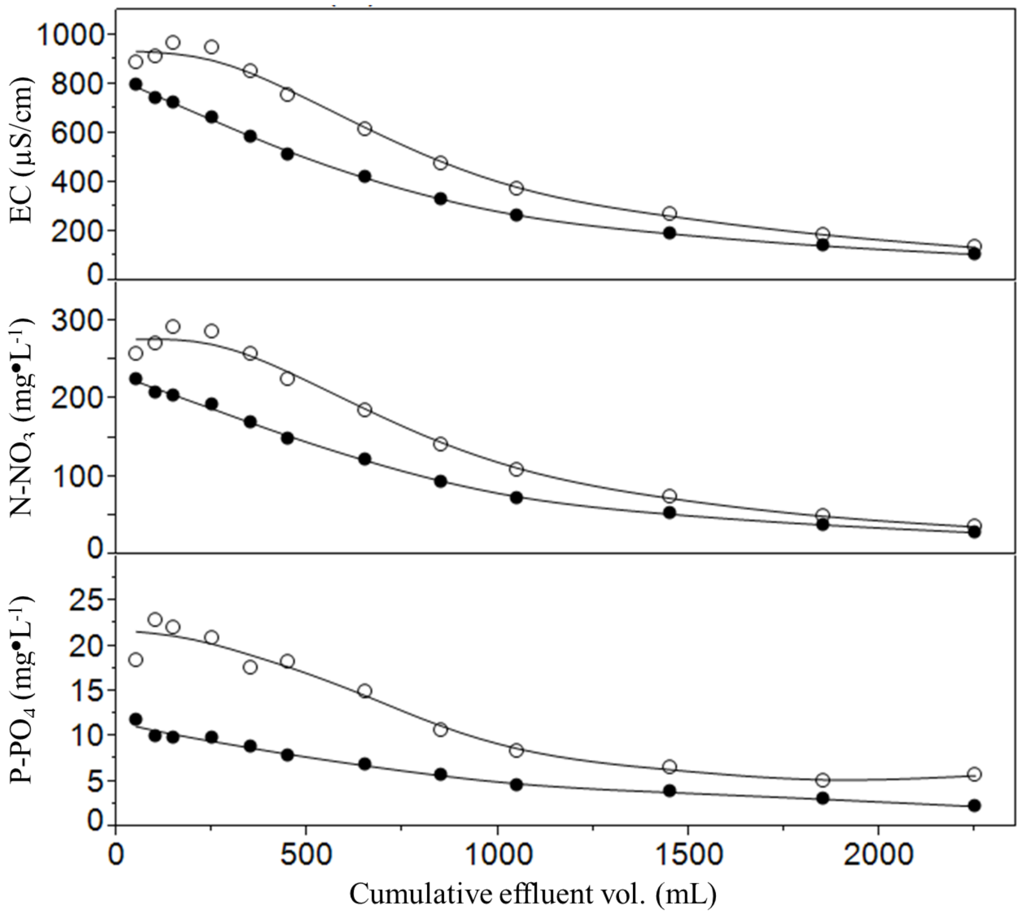

Fig. 3. Exp. 2 release curves showing changes in effluent electrical conductivity (EC), nitrogen ($N\text{-}NO_3$) and phosphorus ($P\text{-}PO_4$) concentration as a function of cumulative effluent volume for fallow, 2.7 L nursery containers with a 9 bark : 1 sand (% by vol.) substrate with a controlled-release fertilizer applied as (○) incorporated or (●) topdressed CRF during irrigation with deionized water (DI) at a rate of 300 mL•min^{-1}.

Conclusion

In summary, the results of these experiments demonstrate the relative rapidity, which water and mineral nutrients may move through and leach from pine-bark based substrates during the irrigation of containerized ornamental crops. The steep moisture gradient observed between the upper (very low moisture content; MC) third of the container profile and the lower (less dry) regions induced an uneven wetting front progression, where applied irrigation water moved through the substrate via channels, which may lead to an uneven post-irrigation substrate moisture distribution and early leaching. This trend was not observed in containers with a more even pre-irrigation moisture distribution, which raises questions about the application of dissolved mineral nutrients via irrigation water (fertigation). Applied fertilizers may be carried through channels and quickly leach before reaching the entire root zone. Fertigation may then be most effectively conducted when the substrate MC is relatively high, with the application of only enough water to displace the volume of water held by the substrate. Similarly, the relatively even movement of water through wet substrates may actually validate the use of the pour-through (PT) procedure for assessing the quantity of post-irrigation substrate available nutrients. If a (PT) were to be conducted in dry conditions, the surface-applied water may channel through the substrate and not provide a good estimation of the available nutrients throughout the substrate, hence the reason a PT is conducted when the substrate is at container capacity.

In controlled column experiments, anions moved through the substrate very rapidly, whereas cation transport was actually reduced due to interaction with pine-bark cation exchange sites. However, the amount of potassium that was retained by the substrate constituted a surprisingly small fraction of the overall cation exchange capacity of the bark. Several factors are likely to occur while solution is flowing through the substrate that affect the movement of solutes. The dispersion of applied ions via flow through macro and micropores, and their diffusion into antecedent pore water while water is flowing through the pores may be factors that limit the potential interaction between solution cations and substrate surface chemistry. Cation exchange may be more likely to occur between irrigation events when conditions are more static. Further research into this phenomena, using an approach similar to those in this study, may be used in horticultural research to better understand the extent to which ion exchange affects the transport of nutrients move through a substrate during irrigation.

The placement of controlled-release fertilizer (CRF) in the substrate profile affected the pattern which nutrients were leached from containers during irrigation. Generally, leachate nutrient concentrations are highest in the first leachate generated and diminishes with continued irrigation. These results were consistent with research that found increased leachate nutrient concentrations, but lower total load leached, at low leachate volumes (or lower leaching fractions). Interestingly, effluent concentrations from dibbled containers rose throughout the first 150 mL of leachate, plateaued and then diminished, suggesting that dibble may be an advantageous method for reducing nutrient leaching when leachate volumes are low.

Research herein provides insight into how the movement of water and dissolved mineral nutrients from applied fertilizers through a pine-bark substrate during the irrigation of containerized crops is affected by production factors such as root growth, ion species and fertilizer placement. Expanding this knowledge base may lead to new recommendations for irrigation and fertilizer management that enhance water and nutrient use efficiency. Reduced nutrient leaching may leave more nutrients available for crop growth while reducing agrichemical contributions in accordance with regulatory goals that seed to reduce non-point source agrichemical contributions. Furthermore, this knowledge may be used to refine existing models that predict how changes in certain production factors will affect the quantity of nutrients leached. Further research is warranted to determine optimal methods for integrating root growth, substrate MC and within-irrigation solute transport principles to maximize both water and nutrient use efficiency.