LEACHING AND RECHARGING OF NUTRIENTS IN PROPAGATION SUBSTRATES

By

ANGELICA CRETU

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To my parents, for instilling in me the confidence that I can accomplish anything I put my mind to and for teaching me to pursue all of my dreams with integrity and purpose

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By

Angelica Cretu

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Leaching of nutrients from substrates occurs in propagation greenhouses. The objective of this research was to quantify the rate of leaching and recharging of nutrients in peat-based propagation substrates, following application of deionized water (DI) or a nutrient solution. Experiments were conducted to (1) quantify nutrient levels in leachate and propagation substrates with different irrigation solutions and initial pre-plant fertilizer amounts applied, (2) quantify how nutrient leaching differed between five fertilizer forms and six commercial substrates, and (3) evaluate plant growth response in nutrient-deficient petunia to a single irrigation with a fertilizer solution that varied in nutrient concentration and volume. Irrigation solutions (DI or 200 mg $N \cdot L^{-1}$) were applied to either a research substrate (70% peat/30% perlite by volume) incorporated with different fertilizers or to commercial substrates. Substrate and leachate electrical conductivity (EC) increased initially, up to approximately 0.5 container capacities (CC) leached, regardless of the irrigation solution applied. Substrate-EC subsequently decreased when substrates were irrigated with DI or increased when irrigated with nutrient solution. At 1.5 CC leached, the substrate-EC was similar to the EC of the applied irrigation solution. Water-soluble fertilizers that varied in nitrate/ammonium ratio leached at a similar rate,

which was more rapid than for polymer-coated, controlled-release fertilizer. Nitogen measured in leachate ranged from 35% (controlled-release) to 94 % for water-soluble fertilizer forms.

When nutrient solutions were applied to nutrient-deficient petunia liners, plant growth and tissue N concentration increased with increased in mg of N applied. A similar growth response was obtained with a lower nutrient concentrations (300 mg $N \cdot L^{-1}$) applied at high volume (1.7 CC) or high (600 or 1200 mg $N \cdot L^{-1}$) nutrient concentration applied at low volumes (0.6 or 1.1 CC). A single fertilizer application of 17N-2.2P-14.1K was sufficient to raise tissue N concentration to the recommended range, but was insufficient for tissue P and K.

These results emphasize the importance of minimizing excessive application of water to reduce leaching and potential runoff during propagation, and the need to apply an irrigation solution leaching 1.5 CC when the goal is to replace the substrate solution.

CHAPTER 1
INTRODUCTION

The floriculture industry represented $4.22B as wholesale value in 2008 (U.S. Department of Agriculture, 2009). Many of these crops are produced by cutting propagation, which is the most common form of asexual propagation and is the dominant method for many important floriculture species such as zonal geranium and poinsettia (Dole and Gibson, 2006). Cuttings are typically propagated with mist systems that require frequent irrigation applications in order to maintain turgidity of cuttings (Dole and Gibson, 2006; Handreck and Black, 2007). The volume of applied water in propagation versus evapotranspiration rate and substrate water holding capacity determines the leaching rate.

Leaching rates vary widely among commercial greenhouses, ranging from 4.5 to 46.1 L per m^2 during a 4-week crop cycle during propagation of herbaceous cuttings (Santos et al., 2008) depending on the method of irrigation. Leaching is important in terms of potential environmental impacts (increased water use and environmental contamination with nutrients and pesticides). Fertilizer management strategy is also affected by leaching, because as leaching rate increases so does the nutrient solution concentration that is required to maintain a target nutrient level in the substrate (Ku and Hershey, 1991; Yelanich and Biernbaum, 1994). Yelanich and Biernbaum (1994) reported that more than 50% of the NO_3–N in an applied nutrient solution can be lost to the leachate, regardless of the fertilizer concentration, at a leaching fraction (defined as the volume of leachate divided by the volume applied) of 0.25.

The rate at which nutrients are leached from a substrate is affected by the physical properties of substrate, irrigation method, duration and frequency of irrigation, and fertilizer form and amounts. An important physical property that affects leaching is the pore architecture, in addition to other properties such as bulk density, total pore space, structural stability, water

retention and rewetting, hydraulic conductivity and diffusivity (Blok and Wever, 2008). Horticultural peat has approximately 9% (by volume) solids, with approximately 54% water and 37% air making up the total pore space of 91%, with decreasing air porosity as decomposition increases (Verdonck et al., 1981; Bruckner, 1997; Blok and Wever 2008). Increased air porosity results in decreased bulk density and water retention and increased oxygen transport and root penetration. Perlite, a common component of greenhouse substrates, can have up to 20% non-connected pores, and the water/solution from these pores is not replaced by irrigation solution flowing through the substrate (Hoag and Price, 1997; Block and Wever, 2008). The solution contained in non-connected pores from perlite together with solution in fine pores in peat is termed immobile water, and nutrients dissolved in the immobile water fraction are not easily leached.

Leaching Process

Leaching of nutrients from containers is a complex process. Kerr and Hanan (1985) reported that leaching occurs by two processes that include either mixing between the substrate and irrigation solutions, or via piston flow. Piston flow would result in the complete removal of the substrate solution by the applied solution, and would occur when mixing between the two solutions is absent. With piston flow, the substrate solution would be completely displaced following leaching of one container capacity. When a solution is applied to a substrate, however, some mixing occurs between the applied and substrate solutions depending on the hydraulic conductivity, degree of saturation, distribution of air and water-filled pore spaces, and diffusivity of the substrate and viscosity of irrigation solutions (Kerr and Hanan (1985), Hoag and Price (1997), Yelanich and Biernbaum (1994)). These factors affect how quickly nutrients in the substrate solution are replaced, and studies have shown that leaching between 1 and 1.5 CC with

deionized water reduces the electrical conductivity (EC) in a substrate in containers to near zero (Kerr and Hanan, 1985; Yelanich and Biernbaum, 1994).

Fertilization Rates in Propagation

In terms of greenhouse Best Management Practices, a goal in fertilization is to minimize runoff while supplying sufficient nutrients for plant needs. However, nutrient leaching occurs readily from soilless substrates (Kerr and Hanan, 1985; Yelanich and Biernbaum, 1994; Ku and Hersey, 1997) particularly with the large volume of water applied as mist during propagation (Dole and Gibson, 2006; Handreck and Black, 2007; Santos et al., 2008). Less nutrient runoff could potentially be achieved by reducing applied nutrients with reduced irrigation volume to match plant and substrate hydration requirements, recycling nutrients in the leachate, timing nutrient supply to correspond with plant rooting and uptake, and use of controlled-release fertilizers (Morvant et al., 2001; Merhaut et al., 2006; Newman et al., 2006; Raviv and Lieth, 2008).

Typical rates of incorporated fertilizer include 0 to 6 g of dolomitic limestone depending on the substrate, initial pH and the crop requirement; 0.6 g of KNO_3 or $Ca(NO_3)_2$, 1.3 g superphosphate, 0.9 g gypsum, and a blend of micronutrients between 0.6 and 0.9 g per L of substrate to supply Fe, Mn, Zn, Cu, B, and Mo (Nelson, 2003). The majority of incorporated fertilizers in propagation substrates are immediately available, water-soluble forms, applied as a solution or granules during substrate mixing. These primarily include nitrate-nitrogen, ammonium, or urea forms. Post-plant fertigation with water-soluble fertilizers in irrigation water typically ranges from 0 to 194 mg $N \cdot L^{-1}$ during plug and cutting propagation (Huang et al., 2002; Santos et al., 2008) depending on crop rooting stage and frequency of fertilizer applications.

Leaching rate may differ depending on the nitrogen ionic form. Fertilizer forms composed of NO_3 - N can be easily lost (Yelanich and Biernbaum, 1994), because of the negative charge

and low anion exchange capacity of peat (Handreck and Black, 2007). Fertilizer forms composed of NH_4 - N may remain longer in the substrate via bonding to cation exchange sites. The cation exchange capacity for peat is moderate to high on a substrate mass basis, at 7 to 13 meq/100 cc (Dole and Gibson, 2006).

Controlled-release fertilizers contain nitrogen and other nutrient in the same forms found in water-soluble fertilizers, in the form of prills covered with a polymer or other film that regulates nutrient release over time. Nutrient release rate from controlled-release fertilizers may also vary depending on formulation. Research has shown significant differences between leaching rate during a 12-month period for various controlled-release products (Donald et al., 2006; Newman et al., 2006). Some negative aspects of controlle- release fertilizers are that the release is not uniform during the release period, and nutrient release rate is not always correlated with plant uptake requirements (Hershey and Paul, 1982). Specifically for propagation of vegetative cuttings, an ideal nutrient release curve would be 4 weeks, which is a shorter duration than for most crops where controlled-release fertilizers are used. Furthermore, use of controlled-release fertilizer is not widespread in small-celled trays because of the difficulty in obtaining uniform distribution between cells.

Nutrient Deficiencies

Leaching of nutrients from propagation substrates affect plant growth and quality. When nutrients are not applied at the required levels or are lost though leaching, nutrient-deficiencies are likely to occur. Common nutrient deficiencies in plants are due to insufficient N, P, and K. In carnation production, N deficiency appears as a yellowish color of the lower leaves, and with time the leaves sizeis reduced, chlorosis increased, and flower production and growth can be adversely affected (Medina, 1992; Dole and Gibson, 2006). Phosphorus represents the energy source for plants and lack of phosphorus results in delay in growth and maturity. Overall the

plants are stunted and sometimes exhibit foliar symptoms such as dark green stems and leaves that often contain red or purple areas (Medina, 1992; Barker and Pilbeam, 2006). Mild phosphorus deficiency resulting from low P concentrations in applied fertilizer is used to produce compact seedling plugs (Huang et al., 2002). Potassium is needed to control water movement between cells; K-deficiency symptoms may appear first as dull grey-green older leaves. In severe cases, cholorosis and necrosis appear at the margins of leaves, along with reduced plant size (Medina, 1992; Barker and Pilbeam, 2006; Handreck and Black, 2008). Nitrogen, P and K are required by plants in large quantities, but all macro and micronutrients are important to plant growth. Shortage of any of these elements will result in less growth (Hewitt and Watson, 1980; Barker and Pilbeam, 2006). In petunias, iron deficiency often occurs when substrate-pH is above 6.5 (Argo and Fisher, 2002), and boron deficiency is also a common environmentally-induced problem when transpiration rate and nutrient uptake are reduced (Styer and Koranski, 1997).

Objectives and Chapters

The overall thesis objective was to quantify the rate of leaching and recharging of nutrients in peat-based substrates that are used in greenhouse propagation, following application of deionized water (DI) or a nutrient solution. Previous research on leaching in greenhouses has focused on potted plants, rather than propagation. Not many studies were focused on leaching and fertilizer concentration in plug and liner trays where the water inputs relative to substrate volume may be much higher than in large containers. The amount of water applied and nutrients lost from propagation substrates need more attention.

In Chapter 1, an experiment was conducted to quantify nutrient levels in leachate and propagation substrates with different initial pre-plant fertilizer levels and irrigation solutions. A peat/perlite substrate (70%/30%, by volume) was incorporated with 2.1 g of dolomitic hydrated

lime, and KNO_3 as pre-plant fertilizer at one of these three rates: 0, 0.6 and 1.2 g per L of substrate. Irrigation solutions (either DI or 200 mg $N \cdot L^{-1}$) were applied to 128-count propagation trays 12 times. After each irrigation, the volume of leachate was quantified and substrate solution samples and leachate samples were collected to determine EC and N concentrations.

In Chapter 2, experiments evaluated how nutrient leaching differed between five fertilizers and six commercial substrates. Previous research cited in Chapter 1 showed rapid leaching from a nitrate-based fertilizer incorporated in a peat/perlite propagation substrate. However, information was not available on how different fertilizer or substrate compositions affected leaching rates. A peat/perlite substrate was blended with five fertilizers differing in N ratios (95% NO_3^- & 5% NH_4^+ & 0% urea, 50% NO_3^- & 50% NH_4^+ & 0% urea, 43% NO_3^- & 57% NH_4^+ & 0% urea, 25% NO_3^- & 25% NH_4^+ & 50% urea, and 57% NO_3^- & 43% NH_4^+ & 0% urea (controlled-release)), and applied at 0.18 g $N \cdot L^{-1}$ and six commercial substrates composed of peat only, peat/perlite, or peat/perlite/vermiculite were irrigated with deionized water twice a day for approximately 14 days. After each irrigation, leachate volume was quantified and substrate solution and leachate samples were collected to determine EC, pH and N-NO_3, N-NH_4, P and K.

In Chapter 3, an experiment was conducted with nutrient-deficient-petunia plants with nitrogen, phosphorus and iron deficiencies visible. The plant growth response was measured following a single irrigation with a fertilizer solution that varied in nutrient concentration and volume. Chapters 1 and 2 provided information about leaching from non-planted systems, although the question if leaching occurs similarly when liners are used was not answered. For this experiment, 6-week old nutrient-deficient petunia liners were irrigated with an irrigation solution containing 0, 300, 600 and 1200 mg $N \cdot L^{-1}$ from 17N-2.2P-14.1K and a micronutrient blend at 5 mg $Fe \cdot L^{-1}$ at three volumes (412.2, 824.4 and 1236.5 mL per propagation tray).

Substrate solution samples were collected 30 minutes and 10 days after treatment application for EC and pH determination. SPAD chlorophyll index, and fresh and dry weights were measured 10 days after treatment application. Nutrient concentration was determined in dry tissue samples.

CHAPTER 2
PRE-PLANT FERTILIZER AND FERTIGATION AFFECT ELECTRICAL CONDUCTIVITY, NITROGEN CONCENTRATION, AND LEACHING OF PROPAGATION SUBSTRATE

Introduction

Propagation of cuttings requires a large irrigation volume to maintain plant turgidity. Leaching rates vary among commercial greenhouses, ranging from 4.5 to 46.1 L per m^2 during a 4-week crop cycle to propagate herbaceous cuttings (Santos et al., 2008). Leaching is important in terms of potential environmental impacts, and also affects the substrate nutrient mass available for optimal plant growth. Yelanich and Biernbaum (1994) reported that more than 50% of the NO_3–N in an applied nutrient solution can be lost in the leachate, regardless of the fertilizer concentration, at 0.25 leaching fractions (leaching fraction is the volume of leachate divided by the volume applied). Research by Ku and Hershey (1991) and Yelanich and Biernbaum (1994) showed that maintaining the same substrate nutrient concentration with increasing leaching rate requires a corresponding increase in applied fertilizer concentration.

Factors that affect leaching are the physical properties of substrate, irrigation method, duration and frequency of irrigation, and fertilizer nutrient carriers. An important physical property that affects leaching is the pore architecture, in addition to other properties such as bulk density, total pore space, resistance to rooting, structural stability, water retention and rewetting, hydraulic conductivity and diffusivity (Blok and Wever, 2008). Horticultural peat typically has approximately 9% (by volume) solids, with approximately 54% water and 37% air making up the total pore space of 91%, with decreasing air porosity as degree of decomposition increases (Verdonck et Boodt, 1981; Bruckner, 1997; Blok and Wever 2008). Increased air porosity results in decreased bulk density and water retention and increased oxygen transport and root penetration. Perlite, a common component of greenhouse substrates, can have up to 20% non-connected pores, and the water/solution from these pores is not replaced by irrigation solution

flowing through the substrate (Hoag and Price, 1997; Block and Wever, 2008). The solution contained in non-connected pores from perlite together with solution in fine pores in peat is termed immobile water, and nutrients dissolved in the immobile water fraction are not easily leached.

Kerr and Hanan (1985) reported that leaching occurs by two processes that include either mixing between the substrate and irrigation solutions, or via piston flow. Piston flow would result in the complete removal of the substrate solution by the applied solution, and would occur when mixing between the two solutions is absent. With piston flow, the substrate solution would be completely displaced following leaching of one container capacity. When a solution is applied to a substrate, however, some mixing occurs between the applied and substrate solutions depending on the hydraulic conductivity, degree of saturation, distribution of air and water-filled pore spaces, diffusion of ions from high to low concentration, ion adsorption, exchange reactions, densities, and diffusivity of the substrate and viscosity of irrigation solutions (Kerr and Hanan, 1985; Yelanich and Biernbaum, 1994; Hoag and Price, 1997). These factors affect how quickly nutrients in the substrate solution are replaced. Studies have shown that leaching between 1 and 1.5 CC with deionized water reduced the electrical conductivity (EC) in a substrate in containers to near zero (Kerr and Hanan, 1985; Yelanich and Biernbaum, 1994).

Previous leaching research has focused on potted plants, which may differ from the nutrient dynamics for plug and liner trays that are characterized by a small cell volume, limited cell depth, and a large container wall surface area relative to substrate volume. For example, research by Argo and Biernbaum (1995, 1996 and 1997) and Frost et al. (2003) found that nutrients applied through surface applications to potted plants were largely retained in the top 2.5-cm of substrate, primarily because of evaporation from the substrate surface. Most plug cells

in propagation trays are 2.5 to 3-cm or less in depth. The average substrate-EC at 3-cm depth was 17-55 % higher than in the delivered nutrient solution in a drip-irrigation study by Ondrasek et al. (2008), which also showed that horizontal salt distribution was highest towards the edge of the container and was lower close to the main rooting zone, immediately under the dripper, and above the drainage hole. The lower salt concentration was caused primarily by intensive leaching of salts near the drainage holes. Salts close to the edges of the container are inaccessible to a less than fully developed root system, causing higher EC in that zone. Substrate-EC is also affected in containers by water flow and plant nutrient uptake, which is in turn mediated by container design, substrate physical and chemical properties, irrigation application rate and duration, and root distributions.

In plant propagation, plant nutrient requirements may be achieved with a combination of pre-plant fertilizer incorporated into the substrate, and/or post-plant fertigation with nutrient solution (Huang et al., 2002). Up to 0.6 g KNO_3 or 0.6 g $CaNO_3$ per L of substrate are typically applied as pre-plant fertilizers in soilless substrates (Nelson, 2003). In a survey of commercial greenhouse businesses, N was applied between 0 and 194 mg $N \cdot L^{-1}$ in the nutrient solution during cutting propagation (Santos et al., 2008). The fate of nutrients in a substrate and leachate therefore likely depends on the pre-plant and irrigation solution fertilizer concentrations, and the solution application rate.

The objective of this study was to quantify changes in EC and N concentration in both substrate and leachate when fertigation was applied to trays of propagation substrate.

Materials and Methods

Experiment 1

The experimental design was a randomized complete block with a factorial design consisting of six treatment combinations from three pre-plant fertilizer levels (0, 0.6 or 1.2 g

KNO_3 per L of substrate) and two applied "irrigation solutions" (either deionized water (0 $dS \cdot m^{-1}$) or 200 mg $N \cdot L^{-1}$ (1.98 $dS \cdot m^{-1}$) derived from reagent KNO_3). The experiment consisted of a total of 75 trays of substrate without plants. Fifteen trays (five trays per pre-plant fertilizer treatment) were used to collect initial EC and N concentrations in the substrate. The remaining 60 trays were divided into six groups of 10 trays per treatment combination. Within each treatment combination, five trays were used for collecting leachate samples and five trays were used for substrate sampling. Application of the irrigation solutions was blocked over time, with one replicate tray for substrate and one replicate tray for leachate measured for each treatment combination on each day. The order as to when each irrigation solution was applied was randomized on each day, resulting in a randomized complete block. On each application day, the irrigation solution (deionized water or KNO_3 solution at 200 mg $N \cdot L^{-1}$) was applied 12 times sequentially to each tray, and the tray was sampled repeatedly, resulting in a repeated measure component to the statistical model.

Greenhouse conditions

The propagation substrate contained 70% (by volume) Canadian sphagnum peat moss (SunShine Peat Moss, Sun Gro Horticulture Distribution Inc., Bellevue, Wash.) and 30% super coarse perlite (Whittemore Co., Cambridge, Mass.). Particle size distribution was measured by passing the samples (n = 15) through a set of sieves for both peat and perlite. The set of mesh screens (Tyler Equivalent 9 mesh 2000 (mesh size 10), W S Tyler (S/N 07249622) 850 (mesh size 20), and W S Tyler (S/N 07249623) 250 (mesh size 60) µM) was hand-shaken with resulting distributions of 19.9, 23.6, 43.3 and, 13.2% for peat, and 60.9, 20.8, 10.7 and 7.6% for perlite. This distribution of particle sizes provided a well-drained substrate (Handreck and Black, 2007) desirable for propagation substrates. Dolomitic hydrated limestone (National Lime and Stone,

Findlay, Ohio) was incorporated at 2.1 $g \cdot L^{-1}$ of substrate, along with 0.15 mL of a surfactant (Psi-Matric, Aquatrols, Paulsboro, NJ.) per L of substrate.

After mixing, the substrates were stored for one day in non-transparent bags until transferred into 50.5 x 25.5 cm, 128-count propagation trays (Blackmore Company, Belleville, Mich.). Volume of substrate per tray was determined by placing the substrate loosely into the trays (ten 128-count propagation trays). The trays were tapped twice on the counter to achieve similar densities across replicates, and to minimize compaction which reduces air porosity (Fermino and Kampf, 2005). Substrate was removed from trays, and placed into a graduated container, tapped twice on the counter (to be consistent with the procedure of filling the trays) and the volume was measured and averaged 3.4L ± 0.07 (± sd). Uniformity of substrate volume per cell was measured using three empty 128-count propagation trays that were filled with 3.4L of substrate and placed in a drying oven at 70°C until a stable weight was achieved. Fifteen cells from each tray were randomly selected and substrate in each cell was measured. The weight of substrate held in each cell averaged 2.82 ± 0.11 (± sd) grams per cell, resulting in a coefficient of variation of 4.02 %.

Container capacity (CC) was determined by direct measurement of the amount of water that could be removed by drying, following saturation and drainage of the container substrate (Raviv et al., 2008). Twelve empty 128-count propagation trays were filled with substrate and then saturated with deionized water by subirrigation (substrate was considered saturated when the water film rose to the surface of the substrate). After saturation, the trays were allowed to drain for 30 minutes. The weights of trays following drainage were measured. The substrate was then removed from the propagation trays, placed in aluminum pans and dried in an oven at 105 ºC until stable weight (to eliminate the hygroscopic water adhering to the particles that can

not be removed by air drying). However, not all hygroscopic water can be removed and the CC obtained does not represent the absolute value (Raviv et al., 2008). The CC was calculated by subtracting the weight of oven-dried substrate from water-saturated substrate. CC was 2051.5 mL ± 41.3 (± sd) per tray or 16.0 ± 0.6 mL per cell. Cumulative container capacity was determined by adding the CC leached with each irrigation.

Trays filled with substrate were brought to container capacity by subirrigation with DI water and kept in the dark at 31ºC for 11 days for complete lime reaction. Trays were brought again to the container capacity by subirrigating with deionized water 30 minutes before the treatments were applied. The initial EC was 0.30, 0.96 and 1.99 $dS \cdot m^{-1}$ for 0, 0.6 and 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant fertilizer treatments, measured in samples collected by plug press method 30 minutes before the fertigation was applied.

Then each tray was irrigated with 3.2 mL per cell of deionized water or KNO_3 solution at 200 mg $N \cdot L^{-1}$, resulting in 2.9 mL leached per cell for each irrigation. The volume of irrigation solution applied was constant over all irrigations and was checked daily by passing collection trays under the stationary boom before the treatments. The volume of irrigation solution from collection trays (38.1 x 15.3 x 5.1 cm) was multiplied by 2.13 (correction factor from collection tray surface to propagation tray surface) to determine the volume applied per propagation tray with each irrigation. A total of 12 irrigations were applied over a 3 h period (8 to 11 a.m.) through a stationary water boom to trays moving (12 cm per second) on a conveyor (Water Tunnel, Blackmore Co., Belleville, MI), with the nutrient solution pumped from a tank with a submersible pump.

The volume of leachate was quantified by collecting the leachate in collection trays placed underneath of propagation trays during irrigations, and the volume was multiplied with

2.13 (the same correction from collection tray area to a propagation tray area) to determine the volume leached per propagation tray. The volume of leachate was expressed as container capacity (CC) leached, which was determined by dividing the volume leached per irrigation by the CC.

Leachate and substrate solution samples were collected for nutrient analysis. Leachate samples (approximately 150 mL) were collected from collection trays. Substrate solution samples (approximately 25 mL) were collected using the plug press method (Scoggins et al., 2002) by pressing down firmly on top of the substrate surface and collecting the solution from the bottom of the pressed plug on each of the five replicate propagation trays per treatment. Each sample represented substrate solution collected from ten cells. Any individual cell per tray was sampled only once. Samples were stored in dark at 5ºC until analyzed for EC and N concentration.

EC was measured with an Orion electrode (Orion 013005MD, Thermo Electron Corporation) connected to an Orion 5Star meter (Thermo Fisher Scientific Inc., MA) for room temperature samples. The meter was calibrated before each set of measurements with 1413 $\mu S \cdot cm^{-1}$ calibration solution (Thermo Electron Corporation).

Nitrogen concentration was measured with an accumate® Nitrate Combination Ion Selective Electrode (Fisher Scientific, Pittsburgh, PA) connected to an Orion 5Star meter. The concentration range of the electrode was between 0.5 and 62,000 $mg \cdot L^{-1}$ NO_3-N ± 2% reproducibility when temperature ranged from 0 to 40° C, and pH ranged from 2.5 to 11, with a slope of 56 ± 3mV/decade. The electrode could interference with ClO_4^-, Cl^-, CN^-, I^-, BF_4^- and organic acids.

The electrode was calibrated before each set of measurements using standard solutions made in-house from 1000 mg NO_3-N·L^{-1} (Ricca Chemical Company, Arlington). The 100 mL standard solutions of 0.5, 10, 100, 200 mg NO_3-N·L^{-1} were prepared daily. Low concentration standard solutions such as 0.5 and 10 mg NO_3-N·L^{-1} were obtained through serial dilution from 100 mg NO_3-N·L^{-1}. Samples received 2 mL of ionic strength adjuster (ISA) solution to reduce standard and collected sample differences in ionic strength. The ISA was 2 M of $(NH_4)_2SO_4$, and was made in-house from reagent-grade ammonium sulfate.

Room temperature samples were diluted with deionized water at 1:1 ratio for leachate samples, and 1:9 ratios for substrate solution samples. These ratios were chosen based on substrate and leachate sample volume, and the sample volume required by the NO_3-N electrode that was 100 mL. The electrode was rinsed with deionized water and dried with a clean tissue before each measurement.

The electrode was also calibrated with solutions made with reagent grade KNO_3 at 1, 5, 10, 20, 50, 100, and 200 mg N·L^{-1} that resulted in a calibration curve of $y = 0.9989x + 0.2153$, where Y axis was the actual N (mg·L^{-1}), and X was the N (mg·L^{-1}) measured with the sensor (i.e. with a slope not significantly different from 1).

Data analysis

Data were analyzed as a randomized complete block design with factorial treatments of pre-plant fertilizer, fertigation, and number of irrigations. Measurement day was a blocking factor, and number of irrigations was analyzed as a repeated measure factor. Test of Effect Slices was conducted for solution and number of irrigation and substrate fertilizer and number of irrigation. The ANOVA was run using Proc MIXED in SAS v. 9.1 (SAS Institute, Cary, NC). The 95 % confidence intervals were determined using standard errors from Proc MIXED.

Experiment 2

A small experiment was conducted to determine if the two sample methods (plug press method (PPM) and saturated media extract (SME)) could affect measured EC and nutrient concentration in the substrate solution.

The experimental design was a randomized complete block with one pre-plant fertilizer level (1.2 g KNO_3 per L of substrate) and two applied "irrigation solutions" (either deionized water (0 $dS \cdot m^{-1}$) or 200 mg $N \cdot L^{-1}$ (1.98 $dS \cdot m^{-1}$) derived from reagent KNO_3). The experiment consisted of a total of 60 trays of substrate without plants.

Greenhouse conditions

The same peat/perlite substrate from the previous experiment was prepared with 2.1 $g \cdot L^{-1}$ dolomitic hydrated lime along with 0.15 mL of water regulating surfactant and 1.2 g KNO_3 per L of substrate. The substrate was then transferred in 128-count propagation trays, brought to container capacity (using the same procedure as in previous experiment) by subirrigation with DI water and incubated for seven days (in dark conditions) for complete lime reaction. After seven days, the trays were brought again to container capacity 30 minutes before the treatments were applied. Twenty trays (ten trays per method of sampling) were used to collect initial EC (seven trays) and N and K concentrations (three trays) in the substrate. Initial EC, N and K were measured (after the trays were brought to the CC the second time) using either the plug press method (Scoggins et al., 2002) or the saturated media extract method (Warncke, 1995), with seven replicates per method for initial EC and with three replicates per method for N and K, respectively. The remaining 40 trays were divided into two groups of 20 trays per treatment combination. Within each treatment combination, ten trays were used for determining EC, N, and K concentrations in samples collected by Plug Press Method and ten trays were used to determine EC, N, and K concentrations in samples collected by Saturated Media Extract. The

irrigation solution (deionized water or KNO_3 solution at 200 mg $N \cdot L^{-1}$) was applied tow times sequentially to each tray prior to sample collection.

The propagation trays were irrigated with 330 mL of either DI water or 200 mg $N \cdot L^{-1}$ from KNO_3 by passing through the stationary boom two times, resulting in a total leachate volume of 355 mL, or 0.34 CC leached. After the second irrigation, substrate-EC was measured with seven replicates (with one tray per replicate) for both irrigation solutions and each method of collecting samples. N and K were measured with three replicates per irrigation solution and method.

EC was measured using the same procedure and sensor as in the previous experiment. Potassium was measured using inductively-coupled plasma (ICP) atomic emission spectrophotometry (Thermo- Jarrell Ash ICAP 61E; Franklin, Mass.). Nitrogen was measured with a Lachat QuikChem AE (Lachat Instruments; Loveland, Col.) at Quality Analytical Laboratories (Panama City, Fl.).

Data analysis

Data were analyzed as a completely randomized design, with factors of two testing methods and two irrigation solutions (DI, or 200 $mg \cdot L^{-1}$ N) using Proc GLM in SAS (SAS Institute, Cary, NC). Least-square means were separated using Tukey's HSD test. The 95 % confidence intervals were determined using standard errors from Proc GLM.

Results

Substrate Electrical Conductivity

There was an interaction of pre-plant fertilizer, irrigation solution and number of irrigations ($P = 0.0159$) for substrate EC (Table 2-1 and Figure 2-1 A). Zero, 1, 2, 3, 4, 5, 6, 7,8 9,10, 11 and 12 irrigations represent the 0.00, 0.17, 0.36, 0.55, 0.74, 0.93, 1.11, 1.30, 1.48, 1.66, 1.84, 2.02, 2.20 cumulative container capacities leached from the substrate. Leachate data are offset in the X-axis in Fig. 2-1 B and D to 0.09, 0.26, 0.45, 0.65, 0.84, 1.02, 1.20, 1.39, 1.57,

1.75, 1.93 and 2.20 because the collection trays accumulated leachate continually whereas the substrate measurements were taken at one point in time. A general trend occurred in two stages: (a) an initial increase in substrate-EC for the first 0.36 CCCL, followed by (b) a gradual convergence of the substrate-EC towards the irrigation solution EC (0 or 1.98 $dS \cdot m^{-1}$) by 1.5 CCCL, regardless of initial pre-plant fertilizer treatment.

With the first two irrigations, or 0.36 CCCL, substrate-EC increased from 1.99 to 2.39 $dS \cdot m^{-1}$ for 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant, and from 0.96 to 1.30 for 0.6 g KNO_3 pre-plant per L of substrate. Irrigation solution did affect substrate-EC at third irrigation, or 0.56 CCCL ($P < 0.0001$, test of effect slices) and continue to affect until the last irrigation applied ($P < 0.0001$).

After the second irrigation the EC decreased for all pre-plant fertilizer treatments when 0 mg $N \cdot L^{-1}$ was applied and increased for all pre-plant fertilizer treatments when 200 mg $N \cdot L^{-1}$ was applied. For substrate with 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant, the substrate-EC stabilized (meaning that there was no change in EC with subsequent CCCL) after the sixth irrigation or (1 CCCL) for the 200 mg $N \cdot L^{-1}$ irrigation solution or eighth irrigation (1.5 CCCL) for 0 g $N \cdot L^{-1}$. For substrate with 0 or 0.6 $g \cdot L^{-1}$ KNO_3 pre-plant, substrate-EC increased to near the solution-EC of 1.98 $dS \cdot m^{-1}$ when irrigated with 200 mg $N \cdot L^{-1}$ solution or decreased to a minimum of 0.1-0.3 $dS \cdot m^{-1}$ when irrigated with DI water after 1.5 CCCL. Pre-plant fertilizer affected the EC up to seventh irrigation ($P < 0.0001$).

Leachate Electrical Conductivity

Leachate-EC (Table 2-1) did not exhibit an interaction of substrate pre-plant fertilizer, irrigation solution and number of irrigations applied ($P < 0.9756$) and showed similar trends to substrate-EC (Figure 2-1 B). Leachate-EC for substrate with 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant irrigated with 200 mg $N \cdot L^{-1}$ solution increased from 2.0 to 2.40 $dS \cdot m^{-1}$ with the first three irrigations or 0.44 CCCL and then decreased to a plateau of 1.98 $dS \cdot m^{-1}$ with the KNO_3 solution or to a

minimum of 0.1-0.3 $dS \cdot m^{-1}$ for DI water. After the ninth irrigation or 1.5 CCCL, leachate-EC was converging with irrigation solution EC for both irrigation solutions. For substrates with either 0 or 0.6 $g \cdot L^{-1}$ KNO_3 pre-plant irrigated with KNO_3, the leachate-EC increased to a plateau of near 1.98 $dS \cdot m^{-1}$ (equal to the solution applied). Leachate-EC decreased to a minimum (close to zero) after the ninth irrigation (or 1.5 CCCL) when DI water. Pre-plant fertilizer treatments no longer affected leachate-EC by the eighth irrigation or 1.5 CCCL ($P = 0.0647$, test of effect slices).

Nitrogen Concentration in Substrate

Substrate N concentration (Table 2-1) did not exhibit interaction of pre-plant fertilizer, irrigation solution and number of irrigations applied ($P < 0.6903$). Concentration of N for the three pre-plant KNO_3 rates of 0.6 and 1.2 $g \cdot L^{-1}$ increased from initial levels of 83 and 165 mg $N \cdot L^{-1}$, respectively, up to a maximum after 0.36 CCCL when DI water was applied (Figure 2-1 C). Substrate-N then decreased and was stable after 1.5 CCCL for all substrates when DI water was applied. For substrates receiving 200 mg $N \cdot L^{-1}$ solution, the N concentrations either decreased (for pre-plant KNO_3 at 1.2 $g \cdot L^{-1}$ of substrate) or increased (for substrates pre-plant with KNO_3 at 0 and 0.6 $g \cdot L^{-1}$) after 0.36 CCCL, and subsequently leveled off at 1.5 CCCL, with substrate-N slightly less than the applied N concentration. Pre-plant fertilizer effect on substrate N was not distinguishable at the eight irrigation or 1.43 CC leached .($P < 0.1037$, test of effect slices).

Nitrogen Concentration in Leachate

Leachate N concentration (Table 2-1) did not exhibit an interaction of substrate pre-plant fertilizer, irrigation solution and number of irrigation ($P < 0.3956$). N concentrations followed a similar pattern to substrate-N (Figure 2-1 D). Concentration of N increased when 200 mg $N \cdot L^{-1}$ was applied and decreased when 0 mg $N \cdot L^{-1}$ was applied. The N concentration was converging

with the N concentration of the irrigation solutions applied at the eight irrigation (or 1.5 CCCL). With 3.4L of substrate per tray, each tray received a total of 280 or 560 mg of N per tray for the 0.6 or 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant rates. N recovered in the leachate from substrate with 0 $g \cdot L^{-1}$ KNO_3 and irrigated with DI water equaled an additional 35.3 mg per tray, representing the N leached from the peat. N recovered in the leachate from the 0.6 or 1.2 g $N \cdot L^{-1}$ KNO_3 pre-plant rates after 2.23 CCCL with DI water (12 irrigations), corrected for the N leached from peat in the 0 $g \cdot L^{-1}$ KNO_3 treatment, equaled 76% and 65% of pre-plant N, respectively.

Results from Experiment 2

Results from Experiment 2 (Table 2-2 and Figure 2-2), showed that substrate testing method affected the measured substrate EC, N, and K levels ($P < 0.0001$). The initial substrate-EC was 1.43 $dS \cdot m^{-1}$ using the PPM, and was either 2.26 or 2.45 $dS \cdot m^{-1}$ after 0.34 CCCL (two irrigations) with DI or 200 mg $N \cdot L^{-1}$, respectively. With the SME method, initial EC was 1.68 $dS \cdot m^{-1}$, and was 1.72 $dS \cdot m^{-1}$ when 200 mg $N \cdot L^{-1}$ applied, but decreased to 1.34 $dS \cdot m^{-1}$ following 0.34 CCCL with DI water. EC measurements would be influenced by the additional 40 mL of DI water added per 213 cm^3 substrate sample in the SME method, compared with the PPM which was extracted from the substrate by a pressing force.

Initial N and K with the PPM and SME were equal (68 mg $N \cdot L^{-1}$ and 246 mg $K \cdot L^{-1}$), but with the PPM these levels increased following leaching with 0.34 CCCL (two irrigations) with DI water (to 105 mg $N \cdot L^{-1}$ and 366 mg $K \cdot L^{-1}$) as well as with 200 mg $N \cdot L^{-1}$ (to 114 mg $N \cdot L^{-1}$ and 410 mg $K \cdot L^{-1}$). In contrast, the SME resulted in a decreased from 68 mg $N \cdot L^{-1}$ and 246 mg $K \cdot L^{-1}$ to 59 mg $N \cdot L^{-1}$ and 224 mg $K \cdot L^{-1}$ following irrigation with DI water and increased to 83 mg $N \cdot L^{-1}$ and 335 mg $K \cdot L^{-1}$ following irrigation with 200 mg $N \cdot L^{-1}$. Both testing methods and fertigation

affected EC, N and K at 0.34 CCCL ($P < 0.0001$), whereas the interaction between testing method and irrigation was significant only for N and K ($P < 0.0001$).

Discussion

An initial increase in EC and N concentration was observed in both the substrate and leachate, which peaked at 0.36 CCCL for substrate and at 0.64 CCCL in the leachate solution. One explanation for the increase in EC and N with the first two irrigations may be method of collecting samples. Experiment 2 showed that when using the PPM at 0.34 CCCL with DI water, EC, N and K were higher than using the SME. Scoggins et al. (2002) found some inconsistency in comparisons of EC, N, and K levels between SME and PPM, but one experiment showed a multiplier of 1.4 to convert EC from the SME to EC from the PPM, and multipliers of 1.85 to 1.80 for N and K, respectively. An important difference in our extraction method from Scoggins et al. (2002) was that the substrate was sampled 30 minutes after irrigation rather than waiting the 60 min recommended for commercial sampling, meaning that there was less time for the substrate and nutrient solution to come to equilibrium and evaporation to occur.

However, the initial increase in EC is not simply an artifact of the testing method because the EC and N levels also increased in the leachate. A similar increase in leachate-EC was also observed by Kerr and Hanan (1985) in their development of leaching curves with a range in substrate types.

Possible causes for the initial increase in leachate EC and N in Experiment 1 include substrate saturation with deionized water just before the treatments were applied, cation and anion exchange from the peat (CEC is moderate to high (13 meq/100cc, (Verdonk et al., 1981; Dole and Gibson, 2006) and AEC is low (Handreck and Black, 2007)), dissolution of salts, and an uneven distribution of salts through the substrate. The 3-hour time for the 2.23 CCCL in this

experiment and the saturated nature of the substrate during leaching, increase the probable role of factors such as water flow through large pore spaces and channels, and dissolution of salts and exchange of cations and anions with the peat, compared with capillary action and diffusion.

Pre-plant fertilizer (KNO_3) was completely dissolved before it was applied to the substrate. In this study, 0.45 and 0.90 g of KNO_3 (for 0.6 and 1.2 $g \cdot L^{-1}$ KNO_3 pre-plant fertilizer treatments, respectively) were dissolved per 100 mL of water, which is much lower than the KNO_3 solubility limit, which is 13.3 $g \cdot 100^{-1}$ mL of cold water (Weast and Melvin, 1981). Fertilizer was thoroughly mixed into the substrate, which was then left for several days to equilibrate, however the salts may have been unevenly distributed between pores. Vertical movement of salts resulting from evaporation would not be expected to play an important role in this experiment, because trays of substrate were kept constantly moist near container capacity in semi-enclosed non-transparent plastic bags until irrigation solutions were applied.

Leaching occurs first from the largest pores of the substrate, which are also most likely to be sampled through pressure extraction using the PPM. As initial substrate saturation and leaching occurred, water content of the large pores would increase. It is possible that as irrigation solution passed through the large pores, salts adsorbed to the peat in large pores were solubilized and moved into the free soil solution, resulting in an increase in initial EC and N. With subsequent increasing through-flow of DI water, EC and N would be expected to decrease (or equilibrate with the EC and N from the 200 $mg \cdot L^{-1}$ N irrigation solution), as was observed. The observation that irrigation solution did not affect initial leachate levels suggests a piston process (Kerr and Hanan, 1985) whereby substrate solution was first leached from the pores in the base of the substrate before mixing occurred.

There was a diminishing returns relationship in which EC and N in the substrate and leachate approached the EC and N of the applied solution with increasing volume of applied nutrient solution. Depending on the statistical method used, after 1.50 to 2.23 CCCL, the substrate and leachate ECs were not significantly different from the EC of the applied solution.

The importance of immobile nutrients is emphasized by the observation that 24 to 35% of N was not recovered in the leachate following 2.23 CC leached. Similar results were reported by Ku et al., (1996) in planted systems. Water can readily pass through the empty space between substrate and container walls, and propagation trays have a high wall surface area relative to substrate volume. Repeated irrigations may form channels through substrate or between substrate and container walls that may facilitate leaching of large amounts of water without totally replacing the substrate solution. In addition, the substrate may become compacted with repeated irrigation and retain less water (Morvant et al., 2001). Unrecovered N may have been retained in the substrate, exchange sites, micro pores, and fractions of micro pores or possibly lost through denitrification (Ku and Hershey, 1997).

Conclusions

These results have practical implications for best management practices for fertilizer and irrigation propagation trays such as (a) minimize leaching by reducing the volume applied or frequency of applications, (b) reduce or eliminate pre-plant fertilizer if leaching is likely to occur (for example slow-rooting cuttings such poinsettia), (c) apply controlled release fertilizer even if is difficult to achieve uniform distribution of fertilizer in small cells, (d) recharge fertilizer when plants are removed from mist and have root system to take up nutrients and (e) when applying or removing excess salts eight irrigations (approximately 1.5 CCCL) with 409 mL should be applied per 128-count propagation tray.

Table 2-1. ANOVA results with P value from PROC MIXED. Data were analyzed as a randomized complete block design with factorial treatments of pre-plant fertilizer (0, 0.6 and 1.2 g KNO_3), irrigation solution (0 and 200 mg $N \cdot L^{-1}$), and number of irrigations (12 irrigations). Measurement day was a blocking factor, and number of irrigations was analyzed as a repeated measure factor. The ANOVA was run using Proc MIXED in SAS v. 9.1 (SAS Institute, Cary, NC).

Effect	Substrate-EC	Leachate-EC	Substrate-N	Leachate-N
Block	0.0050	0.0022	2.3934	18.3055
Solution	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Substrate fertilizer	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Solution*substrate fertilizer	0.7667	0.4271	0.4105	0.5886
Irrigation (nr. of irrigation)	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Solution*irrigation	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Substrate*irrigation	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Solution*substrate fertilizer*irrigation	0.0159	0.9756	0.6903	0.3956

Table 2-2. Electrical conductivity (EC), N and K concentrations determined in substrate solution samples (Experiment 2). Data represent the mean of seven replicate trays for EC and three replicate trays for N and K concentrations. Samples were collected by two sampling methods: plug press method (PPM) and saturated media extract (SME) after two irrigations with either deionized water (DI water) or 200 mg $N \cdot L^{-1}$ derived from KNO_3. The means were separated by Tukey's honestly significant difference test at $P \leq 0.05$.

Method	Irrigation solution	EC ($dS \cdot m^{-1}$)	N ($mg \cdot L^{-1}$)	K ($mg \cdot L^{-1}$)
PPM	DI water	2.25 a	109 b	366 b
PPM	200 mg $N \cdot L^{-1}$	2.45 a	117 a	410 a
SME	DI water	1.34 c	63 d	224 d
SME	200 mg $N \cdot L^{-}$	1.72 b	87 c	335 c

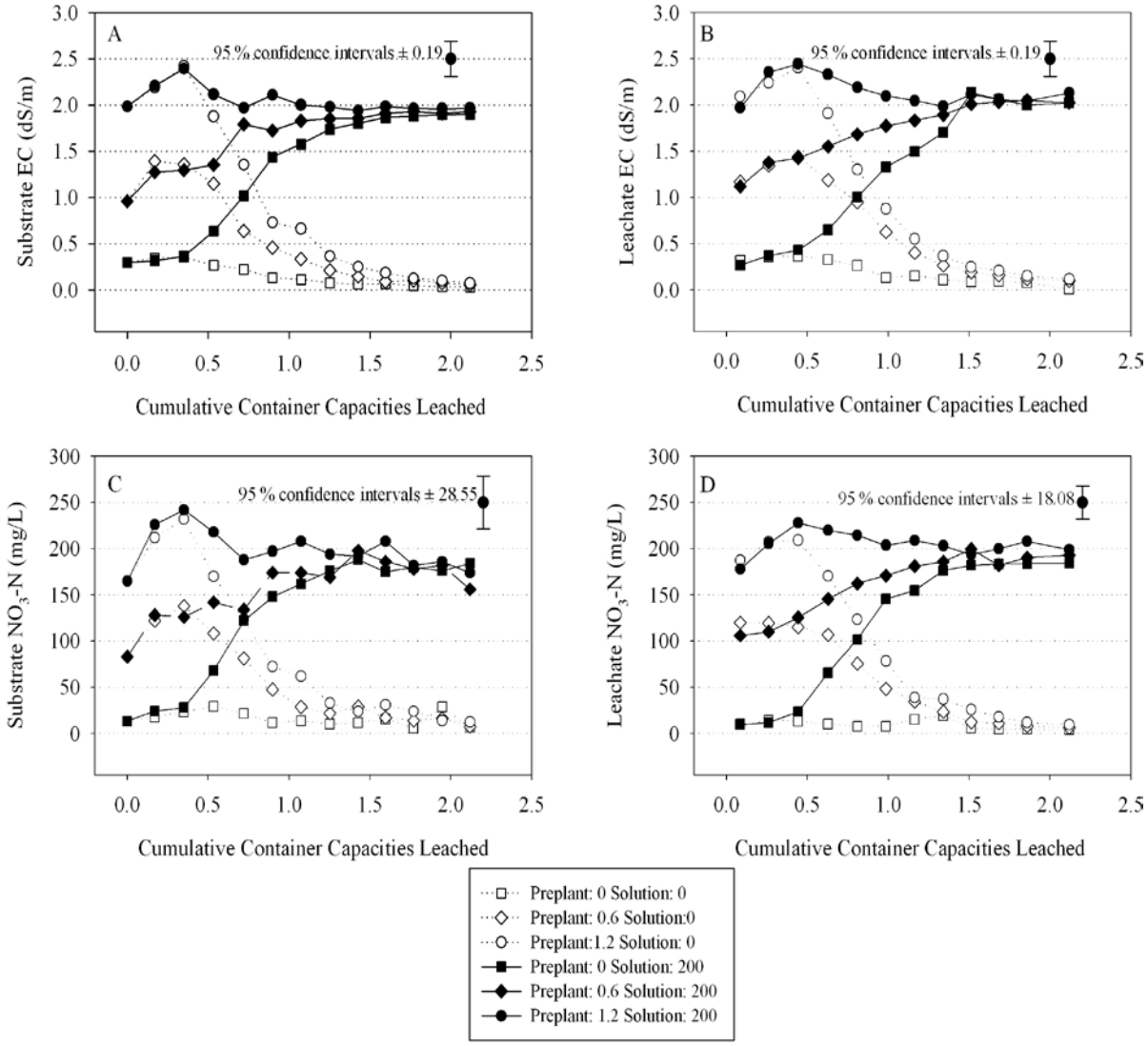

Figure 2-1. Electrical conductivity (EC) and N concentration in substrate and leachate. Changes in electrical conductivity in substrate (A) and leachate (B), and changes of nitrate-N in substrate (C) and leachate (D), following 12 irrigations with either deionized water or 200 mg $N \cdot L^{-1}$ from KNO_3. EC and nitrate-N were measured after each irrigation and averaged for 5 individual propagation trays (n=5) per cumulative container capacity leached.

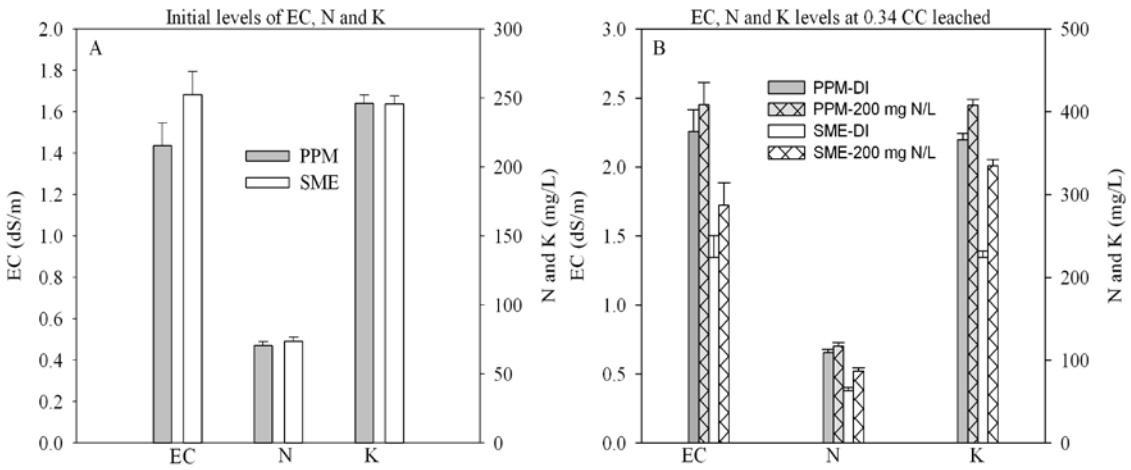

Figure 2-2. Electrical conductivity (EC), nitrogen and potassium concentrations from Experiment 2. Initial values (A) of EC, N and K, and (B) EC, N and K following 2 irrigations (or 0.34 CC leached) with either deionized water or 200 mg $N \cdot L^{-1}$ from KNO_3, determined with two testing methods (plug press method (PPM) or saturated media extract (SME)). EC, N, and K data represent the mean of 7, 3, or 3 samples, respectively, per testing method and irrigation solution ± 95 % confidence intervals.

CHAPTER 3
LEACHING OF NUTRIENTS FROM PROPAGATION SUBSTRATE USING DIFFERENT SUBSTRATE COMPONENTS AND INCORPORATED FERTILIZERS

Introduction

In terms of greenhouse Best Management Practices, a goal in fertilization is to minimize runoff while supplying sufficient nutrients for plant needs. However, nutrient leaching occurs readily from soilless substrates (Chapter 2, Kerr and Hanan, 1985; Yelanich and Biernbaum, 1994; Ku and Hersey, 1997) particularly with the large volume of water applied as mist during propagation (Dole and Gibson, 2006; Handreck and Black, 2007; Santos et al., 2008). Less nutrient runoff could potentially be achieved by reducing applied irrigation volume to match plant hydration requirements, recycling nutrients in the leachate, timing nutrient supply to correspond with plant rooting and uptake, and use of controlled-release fertilizers (Morvant et al., 2001; Merhaut et al., 2006; Newman et al., 2006; Raviv and Lieth, 2008).

Nutrients are primarily supplied during cutting propagation as pre-plant incorporated fertilizer and/or post-plant water soluble fertilization. Typical rates of incorporated fertilizer are 0 to 6 g of dolomitic limestone depending on the substrate initial pH and the crop requirements, 0.6 g of KNO_3 or $Ca(NO_3)_2$, 1.3 g superphosphate, 0.9 g gypsum, and a blend of micronutrients between 0.6 and 0.9 g per L of substrate to supply Fe, Mn, Zn, Cu, B, and Mo (Nelson, 2003). The majority of incorporated fertilizers in propagation media are immediately available, water-soluble forms applied as a solution or solid during substrate mixing, which primarily include nitrogen in the nitrate, ammonium, or urea forms. Post-plant fertigation with water-soluble fertilizers typically ranges from 0 to 194 mg $N \cdot L^{-1}$ during plug and cutting propagation (Huang et al., 2002; Santos et al., 2008) depending on crop rooting stage and whether fertilizer is applied with every irrigation or not.

Leaching rate may differ depending on the nitrogen ionic form. Fertilizer forms based on NO_3-N can be easily lost (Yelanich and Biernbaum, 1994), because of the negative charge and low anion exchange capacity of peat (Handreck and Black, 2007). Fertilizer forms based on NH_4-N may remain longer in the substrate via bonding to cation exchange sites. The cation exchange capacity for peat is moderate to high on a substrate mass basis, at 7 to 13 meq/100 cc (Dole and Gibson, 2006).

Controlled-release fertilizers contain nitrogen and other nutrients in the same forms found in water-soluble fertilizers, in the form of prills covered in a polymer or other film that regulates nutrient release over time. Nutrient release rate from controlled release fertilizers varies depending on formulation. Research has found significant differences between leaching rate during a 12-month period for various controlled-release products (Donald et al., 2006; Newman et al., 2006). Some negative aspects of controlled release fertilizer are that the release is not uniform during the release period, and nutrient release rate is not always correlated with plant uptake requirements (Hershey and Paul, 1982). Specifically for propagation of vegetative cuttings, an ideal nutrient release curve would probably be 6 weeks, which is a shorter duration than for most crops where controlled-release fertilizers are used. Furthermore, use of controlled-release fertilizer is not widespread in small-celled trays because of the difficulty in obtaining uniform distribution between cells.

Previous research (see Chapter 2) found 64 and 75% of N were recovered in leachate from a water-soluble pre-plant fertilizer following leaching of 2.2 CC, with the EC near zero after leaching 1.5 CC. However, in that study we only included a nitrate-based fertilizer (KNO_3) as the incorporated fertilizer, in one substrate (70% peat/30% perlite), and did not examine whether this pattern of leaching was consistent with commercially-used substrates that differ in their

ratios of peat, perlite, vermiculite, and other components which would affect the pore architecture and cation exchange capacity. The objective of this study was therefore to quantify how nutrient-leaching curves differed between (1) five different fertilizer forms and (2) six commercial propagation media when irrigated with deionized water.

Materials and Methods

Fertilizer Form Experiment

The propagation substrate contained 70% (by volume) Canadian sphagnum peat moss (Sun Gro Horticulture, Canada Ltd.), 30% perlite, dolomitic limestone, gypsum and wetting agent, and had an initial electrical conductivity (EC) of 0.6 $dS \cdot m^{-1}$ determined by plug press method (Scoggins et al., 2002). The substrate received one of five "pre-plant fertilizer" formulations, which differed in their element concentrations and fertilizer salts (Table 3-1). Each pre-plant fertilizer was incorporated into the substrate at 0.18 g $N \cdot L^{-1}$ (based on a recommendation of 0.18 g $N \cdot L^{-1}$ derived from KNO_3 or $Ca(NO_3)_2$ (Nelson, 2003)). The control treatment was the same substrate without pre-plant fertilizer. The experiment was a completely randomized designed, with six treatments (five fertilizer forms and one non-fertilized control), one irrigation solution (deionized water, EC = 0 $dS \cdot m^{-1}$) and 12 trays per fertilizer treatment (six replicate trays were used to quantify leachate and collect leachate samples and six replicate trays were used to collect substrate solution samples).

Commercial Substrate Experiment

Six commercial substrates were used for this experiment that differed in their components (peat only, peat/perlite, or peat/perlite/vermiculite) and nutrient concentrations (Table 3-2). The control treatment was the same 70% peat/30% perlite substrate used in the fertilizer form experiment, without any pre-plant fertilizer. The experiment had a completely randomized design with seven treatments (six commercial substrates and one control substrate) and eight

replicate trays per treatment (four trays for leachate, and four replicates for substrate measurements). The experimental unit was a 128-count propagation tray irrigated with deionized water twice per day for 14 days.

Greenhouse conditions

The 128-count propagation trays (52.5 x 26 cm, Blackmore Company, Belleville, MI) lacked vent holes on the upper surface, assuring that leachate was only collected from the drainage openings in the bottom of cells. Trays were filled with the corresponding substrate, and were then brought to the container capacity though sub-irrigation (using the same procedure as in Chapter 2) one day before the treatments were applied. Container capacity (determined using the same procedure as in Chapter 2) for commercial substrates and research substrate (Substrate G is the control substrate) are presented in Table 3-2. After saturation, the trays were placed randomly on benches and covered with a polyester fabric and kept under mist (with a frequency of seven seconds every 60 minutes) to reduce evapotranspiration. Trays were then irrigated with deionized water (EC = 0 $dS \cdot m^{-1}$) twice per day (at 8 am and 2 pm) for 14 days for the Fertilizer Form Experiment and 12 days for Commercial Substrate Experiment. Each tray was irrigated with 542 mL per irrigation, equivalent to 4.2 mL per cell, and the irrigation solution was applied through a stationary boom (Blackmore Co., Belleville, MI) to trays moving with a speed of 13 seconds per meter on a variable-speed conveyer belt, with irrigation solution pumped from a tank with a submersible pump.

The volumes applied and leached (Table 3-2) were determined using the same procedures described in Chapter 2. Leachate and soilless substrate solution samples were collected after each irrigation for 4 days (for Fertilizer Form Experiment) and 5 days (for Commercial Substrates Experiment), and once a day (in the morning) for the remainder of the experiments. Each substrate sample (25 mL), was collected by pressing down firmly on the top of the

substrate surface and collecting the solution from the bottom of the pressed plug for each of the six (Fertilizer Form Experiment) or four (Commercial Substrate Experiment) replicates per treatment (Scoggins et al., 2002). Any particular cell from the propagation trays was sampled only once.

Leachate was retained in collection trays (38.1 x 15.3 x 5.1 cm) placed underneath the propagation trays to determine leachate volume and collect leachate samples. Two leachate samples (25 mL each) were collected with each irrigation cycle for measurement of EC and pH, and were combined as cumulative leachate samples for each tray, for N, P, and K analysis at the end of the experiments. Substrate and leachate samples were kept cool (5°C) in dark until analyzed.

Electrical conductivity was determined with a Horiba EC meter (model B-173, Horiba Ltd., Japan). The electrode was calibrated before each set of measurements with 1413 $\mu S \cdot cm^{-1}$ calibration solution (Thermo Electron Corporation), and pH was measured with a Dual pH meter (Spectrum Technologies, 12360 South Industrial Dr., East Plainfield, Ill), with two calibration points: 4.0 and 7.0 using buffer standard solutions (Orion Application Solutions, Thermo Electron Corporation). The meters were calibrated before use.

Cumulative leachate samples were analyzed for P and K using inductively-coupled plasma (ICP) atomic emission spectrophotometry (Thermo-Jarrell Ash ICAP 61E; Franklin, Mass.). Nitrogen was analyzed using a Lachat QuikChem AE (Lachat Instruments; Loveland, Col.). Both ICP and Lachat analyses were performed by Quality Analytical Laboratories, Panama City, Florida.

Data analysis

All data were analyzed as a completely randomized design, with the number of irrigation passes analyzed as a repeated measure. Proc MIXED in SAS (SAS Institute, Cary, NC) was used for statistical analysis with 95% confidence intervals for mean comparison. The means were separated using Tukey's Honestly Significant Difference test at $P \leq 0.05$. Pairwise Multiple Comparison was used to determine the significance difference between treatments and control (Dunnett test).

Results and Discussion

There was an interaction of pre-plant fertilizer and number of irrigation passes on substrate-EC ($P = 0.0243$, for Fertilizer Form Experiment), or substrate and number of irrigation passes ($P < 0.0001$, for Commercial Substrate Experiment). There was an interaction effect of pre-plant fertilizer and number of irrigation passes on leachate-EC ($P < 0.0001$, for Fertilizer Form Experiment), or substrate and number of irrigation passes ($P < 0.0001$, Commercial Substrate Experiment). The maximum substrate-EC values generally occurred after 0.5 CCCL in both experiments, indicating increased dissolved nutrient concentration compared with the nutrient concentration in the substrate solution at time zero. In the Fertilizer Form Experiment (Figure 3-1), the substrate-EC ranged from 1.55 to 2.88 $dS \cdot m^{-1}$ at 0.5 CCCL, with the exception of controlled-release fertilizer and control treatments, where substrate-EC decreased after the first irrigation. Commercial substrates (Figure 3-2) were similar except for substrate C that had 326 mg $K \cdot L^{-1}$ in the substrate differed widely in their substrate-EC level at 0.5 CC leached. Substrate C had the highest reported pre-plant fertilizer (Table 3-2), and the maximum substrate-EC of 5.64 $dS \cdot m^{-1}$ at 0.5 CCCL and this treatment exceeded the recommended level ranging from 0.75 to 2 $dS \cdot m^{-1}$ depending on the stage of growth (Styer and Koranski, 1997). For

Fertilizer Form Experiment, leachate-EC followed similar trends with substrate-EC, with values ranging from 1.5 to 2.5 at 0.7 CCCL with the exception of controlled-release that was 0.72 $dS \cdot m^{-1}$. Commercial substrate leachate-EC ranged from 1.1 to 5.64 $dS \cdot m^{-1}$ when 0.7 CCCL, and substrate and leachate-EC decreased with increasing number of irrigation passes after 0.7 CCCL. Following leaching of 1.5 CCCL the commercial substrate-EC ranged from 0.3 to 0.5 $dS \cdot m^{-1}$. By the end of both experiments, EC was between 0.1 to 0.3 $dS \cdot m^{-1}$ for substrate and leachate.

There was an interaction for substrate-pH for fertilizer and number of irrigation passes ($P = 0.0243$, Fertilizer Form Experiment) or substrate and number of irrigation passes ($P < 0.0001$), Commercial Substrate Experiment). Leachate-EC exhibited similar interactions: fertilizer and number of irrigations ($P < 0.0001$, Fertilizer Form Experiment) or substrate and number of irrigation passes ($P = 0.0014$, Commercial Substrate Experiment). The pH tended to increase as EC decreased in both the substrate and leachate (Figure 3-1 C and D and Figure 3-2 C and D). In the Fertilizer Form Experiment, substrate-pH was initially highest for the no-fertilizer control followed by the controlled release fertilizer treatment. At the end of the Fertilizer Form Experiment, the no-fertilizer control also had the highest substrate-pH, and the controlled-release fertilizer (which had a slightly higher substrate-EC than control, Figure 3-1 A) had the lowest substrate-pH (7.2). In all cases, the final substrate-pH in the Fertilizer Form Experiment was above the recommended value of 5.4 to 6.6 (depending on crop species) for container substrates (Argo and Fisher, 2002), emphasizing the linkage between substrate-EC and substrate-pH. There was no obvious effect of N form (nitrate, ammonium, or urea) on substrate-pH in the Fertilizer Form Experiment, consistent with results from Bishko et al. (2002, 2003) with experiments in a peat-perlite substrate in the absence of plants. The leachate-pH tended to finish higher than substrate-pH in both experiments, mainly because of an unexplained decline in

substrate-pH after 4 CCCL. In the Commercial Substrate Experiment, the lowest substrate and leachate-pH levels at the end of the experiment occurred in substrates that also had lower initial pH levels. Substrate C, with the highest initial substrate-EC levels had the lowest initial substrate-pH. A drop in substrate-pH occurred in substrates A, C and E at the end of the Commercial Substrate Experiment, but the pH values in other substrates were above the recommended range (Argo and Fisher, 2002).

Amounts of N, P, and K leached (Tables 3-3 and Table 3-4) during both experiments were affected by the fertilizer type (Fertilizer Form Experiment) or substrate (Commercial Substrates Experiment) ($P < 0.0001$). The five fertilizer form treatments leached more than the unfertilized control (tested using Dunnett's test). Between the three water-soluble fertilizer types that contained only nitrate and ammonium, the leached total-N (Table 3-3) was slightly higher for the high-ammonium fertilizer, which suggests that cation exchange did not play a significant role in leaching of N. Nitrate-N leached was similar between the 95 % NO_3-N, 50% NO_3-N% and 43 % NO_3-N fertilizer suggesting that some nitrification of NH_4-N occurred. The 25% NO_3^- + 25% NH_4^+ + 50% urea water soluble fertilizer resulted in a lower measurement of leached N than the other three water-soluble fertilizers. Urea has been reported by the manufacturer to release 15-20% N at 25°C in 4 weeks, meaning that 15-20 % of total N from urea will be readily available for plant uptake (Handreck and Black, 2008). However, our experiment was only conducted for 14 days, and we did not measure the urea-N component directly in the substrate or leachate (only NO_3-N and NH_4-N). During this short experiment, there was apparently little if any N released in these forms from urea through urea hydrolysis. Total N leached from the controlled release fertilizer was less than 1/10 the amount of the water-soluble nitrate and ammonium fertilizers (Table 3-3).

Nitrogen measured in leachate at the end of the experiment from research substrate (Table 3-3) ranged from 35 % from controlled release treatment up to 95% from 50% NO_3^- + 50% NH_4^+ + 0% urea. Results from Chapter 2 showed 65 and 76% N recovered from NO_3-N based fertilizer after 2.2 CCCL. Other studies showed smaller amounts of N recovered from planted-systems. Morvant et al. (2001) reported N recovered up to 20% for controlled-released fertilizer and up to 50% when water soluble fertilizer was applied to geraniums. Yelanich and Birnbaum (1994) reported more than 50% of N recovered from NO_3-N based fertilizer applied to poinsettias. Santos et. al (2008) reported 45% N lost during cutting propagation. Unrecovered N was probably primarily retained by the substrate on exchange sites and in small substrate pores by-passed by the irrigation solution (Hoag and Price, 1997).

Leaching of P was highest for the 43% NO_3^- + 57% NH_4^+ + 0% urea, which was the only water-soluble fertilizer with P supplied as ammonium phosphate. Other water-soluble fertilizers may have had lower solubility from calcium phosphate at the higher substrate-pH levels. Leached K (Table 3) ranged from 0.83 to 3.47 $g \cdot m^{-2}$, but there was no obvious trend as to why differences in K occurred between fertilizer types.

Nutrients leached ranged widely between commercial substrates (Table 3-4), by a factor of 270 for total-N, 16 for P, and 2.5 for K. In comparison, reported N application rates varied by a factor of 4.4 (Table 3-2), suggesting that either reported incorporation rates were not accurate (for some substrates the N, P and K measured in leachate at the end of the experiment were higher than amounts of these elements reported as incorporated) or there were effects of fertilizer and substrate type. Commercial substrate that included vermiculite, which would be expected to have higher cation exchange capacity than peat/perlite blends (Substrates B, E, and F), had the highest NH_4-N and K leaching rates. Substrates A and E had low N levels recovered in the

leachate, however the 30-fold differences between Substrate B and E, which both contained 80% peat/20% perlite is unexplainable.

Conclusions

The general trend in both experiments was of an initial increase in substrate-EC, followed by decreasing substrate-EC values with increasing irrigation to near zero following leaching of 1.5 CC. These results were consistent with those from Chapter 2, and also previous research on nutrient leaching from soil-less substrates (Kerr and Hanan, 1985; Merhaut et al., 2006 and Newman et al., 2006).

These results have practical implications for Best Management Practices. The consistent trend in leaching of water-soluble nutrients, despite a wide range of fertilizer forms and commercial substrate products, indicates that leaching rate was not greatly affected by cation exchange capacity (which was reported to be low to moderate) or ion form. This result emphasizes the importance of reducing leaching by matching irrigation and fertilizer rates to crop needs.

A high rate of (or perhaps any) pre-plant fertilizer is not justified in propagation before root growth occurs, given the high volume of water applied to cuttings to maintain turgidity, and the lack of roots present for nutrient uptake. Controlled-release fertilizer would be a better alternative as a pre-plant fertilizer compared with a water-soluble fertilizer in propagation if there is a way to evenly distribute small prills between cells on the tray, and nutrient release rate is rapid (4 to 6 weeks for most herbaceous cuttings). Given currently-available fertilizer products, however, controlled release fertilizers are only suitable for propagation of larger plant material (particularly woody plants) grown for a longer period than a 6-week crop cycle.

Table 3-1. Nutrients (%) present in fertilizer. Controlled-release fertilizer was a resin multicoated fertilizer with three month time release at 25°C.

	Fertilizer chemical composition (%)															
Fertilizer	NO_3-N	NH_4-N	Urea-N	P	K	Ca	Mg	SO_4-S	Fe	Mn	Cu	Zn	B	Mo	Applied rate ($g \cdot L^{-1}$)	EC ($dS \cdot m^{-1}$)
95% NO_3^- & 5% NH_4^+ & 0 % urea[Z]	5.6	0.3	0.0	0.8	3.3	10.7	0.4	4.1	0.330	0.066	0.044	0.066	0.018	0.009	3	1.6
50% NO_3^- & 50 % NH_4^+ & 0 % urea[y]	3.0	3.0	0.0	0.8	2.0	4.5	0.4	5.2	0.330	0.066	0.044	0.066	0.018	0.009	3	1.3
43 % NO_3^- & 57 % NH_4^+ & 0 % urea[X]	8.6	11.5	0.0	2.7	11.7	0.0	1.3	1.8	0.100	0.050	0.025	0.050	0.025	0.100	0.9	1.3
25% NO_3^- & 25% NH_4^+& 50% urea[V]	1.5	1.5	3.0	0.8	3.3	4.5	0.4	5.2	0.330	0.066	0.044	0.066	0.018	0.009	3	1.4
57% NO_3^- & 43% NH_4^+ & 50% urea[V](Controlled-release)	10.3	7.7	0.0	2.6	10.0	0.0	1.2	2.3	0.33	0.066	0.000	0.007	0.025	0.007	1	0.7

Z: Derived from calcium nitrate and calcium phosphate, potassium nitrate, potassium sulfate, magnesium sulfate, boric acid, iron EDTA, magnesium sulfate, copper sulfate, sodium molybdate and zinc sulfate.

Y: Derived from calcium nitrate and calcium phosphate, potassium nitrate, potassium sulfate, magnesium sulfate, boric acid, iron sulfate, magnesium sulfate, capper sulfate, copper sulfate, sodium molybdate and zinc sulfate.

X: Derived from ammonium nitrate, calcium phosphate, potassium sulfate, magnesium sulfate, boric acid, iron sulfate, manganese sulfate, copper sulfate, sodium molybdate and zinc sulfate.

W: Derived from ammonium nitrate, ammonium phosphate, potassium nitrate, potassium sulfate, magnesium oxide, sodium borate, iron EDTA, manganese sulfate, sodium molybdate and zinc sulfate.

V: Derived from ammonium nitrate, calcium phosphate, potassium sulfate, magnesium sulfate, urea formaldehyde, boric acid, iron sulfate, manganese sulfate, copper sulfate, sodium molybdate and zinc sulfate.

Table 3-2. Commercial substrates and research substrate (substrate G) components, fertilizer concentration applied ($g \cdot L^{-1}$ of substrate), electrical conductivity (EC), pH, volume of substrate per tray, container capacity (CC) and volume leached per tray per irrigation. Data represent the mean of 4 replicate trays ± sd. All fertilizers were applied as granular or liquid nitrate or ammonium-based water-soluble forms, with the exception of Substrate C that included both granular water-soluble and controlled-release fertilizer forms. Details on concentrations of lime, gypsum amendments, and the specific nutrient salts in commercial substrates was proprietary information.

Substrate code and reported pre-plant mg of N, P, or K per L of substrate	Substrate composition	Reported lime and gypsum amendments	EC ($dS \cdot m^{-1}$)	pH	Volume substrate (mL/tray)	CC (mL/tray)	Volume leached (mL/tray and irrigation)
A (66N-33P-110K)	100% peat	calcitic limestone	1.63 ± 0.08	6.2	3450 ± 147	2176 ± 69	440 ± 24
B (61N-32P-122K)	80% peat + 20% perlite	dolomitic limestone, gypsum	1.30 ± 0.24	4.1	3662 ± 95	2141 ± 56	424 ± 30
C (136N-163P-326K)	70%peat +20% perlite +10% vermiculite	calcitic limestone, gypsum	2.12 ± 0.05	5.1	3962 ± 48	2320 ± 94	439 ± 30
D (82N-31P-86K)	85% peat +10% perlite +5% vermiculite	calcitic and dolomitic limestone	0.82 ± 0.05	5.3	3975 ± 171	2154 ± 67	441 ± 29
E (31N-25P-145K)	80% peat + 20% perlite	calcitic limestone	1.11 ± 0.05	5.1	3850 ± 100	2270 ± 37	438 ± 36
F (41N-11P-68K)	60% peat + 40% perlite	calcitic limestone	1.20 ± 0.11	5.6	3525 ± 96	2047 ± 58	421 ± 25
G (0N-0P-0K)	70% peat + 30% perlite	dolomitic limestone, gypsum	0.62 ± 0.12	4.6	3425 ± 96	2207 ± 54	434 ± 38

Table 3-3. Nutrient concentration ($g \cdot m^{-2}$) leached during 28 irrigations when deionized water (EC = 0 $dS \cdot m^{-1}$) was applied, for fertilizer form experiment. To determine the nutrient concentrations per L of substrate, divide the nutrient concentration by 25 (25 L of substrate per m^{-2}). N represents NO_3-N and NH_4-N. Data represent the mean of six replicates per treatment. The means were separated by Tukey's honestly significant difference test at $P \leq 0.05$.

						(%) Recovered		
Fertilizer type	NO_3-N ($g \cdot m^{-2}$)	NH_4-N ($g \cdot m^{-2}$)	Total N ($g \cdot m^{-2}$)	P ($g \cdot m^{-2}$)	K ($g \cdot m^{-2}$)	N	P	K
95% NO_3^- & 5% NH_4^+ & 0% urea	3.97 a	0.02 c	3.99 b	0.27 c	2.47 b	79.16	41.85	88.06
50% NO_3^- & 50% NH_4^+ & 0% urea	3.42 a	1.29 a	4.72 a	0.43 b	2.60 b	94.88	67.76	92.88
43% NO_3^- & 57% NH_4^+ & 0% urea	3.82 a	0.67 b	4.49 ab	0.52 a	3.47 a	89.89	80.7	119.22
25% NO_3^- & 25% NH_4^+ & 50% urea	1.92 b	0.57 b	2.47 c	0.24 c	1.87 c	47.35	36.8	64.36
57% NO3- & 43% NH4+ & 0% urea (controlled-released)	1.91 b	0.04 c	1.95 c	0.07 d	0.83 d	35.45	9.83	23.54
0% NO3- & 0% NH4+ & 0% urea (control)	0.27 c	0.02 c	0.29 d	0.01 e	0.21 e	0.00	0.00	0.00

* N, P and K recovered from control treatment were subtracted from each pre-plant fertilizer treatment to obtain only the nutrients leached from fertilizer.

Table 3-4. Nutrient concentrations ($mg \cdot m^{-2}$) leached from commercial substrates. Data represent the mean of four replicates per treatment. To determine the nutrient concentrations per L of substrate, divide the nutrient concentration by 25 (25 L of substrate per m^{-2}).

Substrate	NO_3-N ($g \cdot m^{-2}$)	NH_4-N ($g \cdot m^{-2}$)	N ($g \cdot m^{-2}$)	P ($g \cdot m^{-2}$)	K ($g \cdot m^{-2}$)
Substrate A	1.77 c	0.36 c	2.14 c	41.85 bc	16.93 c
Substrate B	19.65 b	2.64 b	22.30 b	74.97 b	23.36 b
Substrate C	49.92 a	4.20 a	54.12 a	329.00 a	27.28 a
Substrate D	10.28 bc	0.47 c	0.20 bc	48.46 bc	18.06 c
Substrate E	0.84 c	0.00 c	0.84 c	20.91 c	11.40 d
Substrate F	9.26 bc	0.01 c	9.27 bc	21.11 c	11.25 d
Substrate G (research substrate)	1.35 c	0.00 c	1.35 c	14.12 c	0.74 e

The means were separated by Tukey's honestly significant difference test at $P \leq 0.05$.

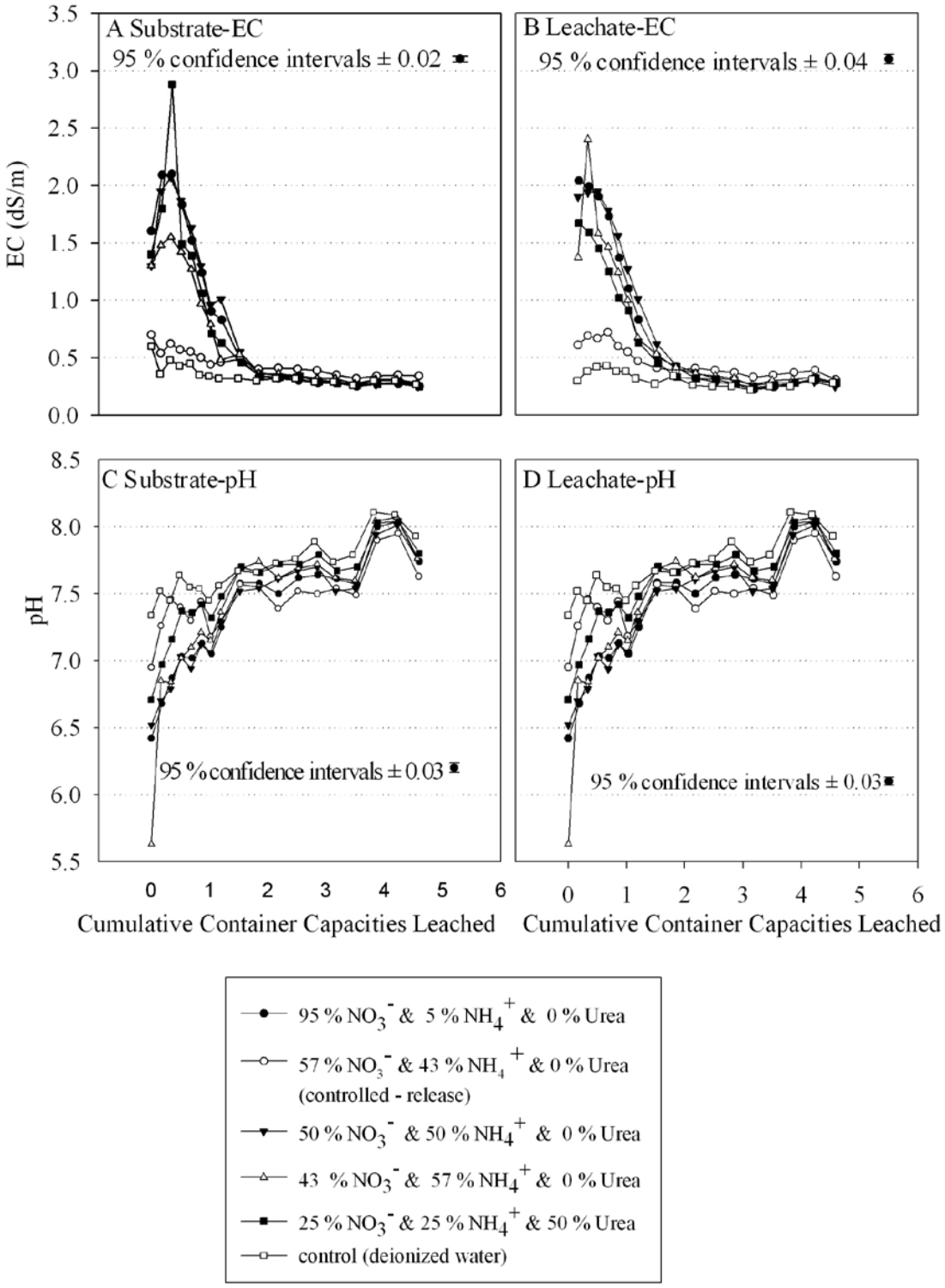

Figure 3-1. Substrate electrical conductivity (EC) and pH in Fertilizer Form Experiment. Substrate-electrical conductivity (A), (B) leachate-EC, (C) substrate pH and (D) leachate-pH were determined in samples collected over 28 irrigations when deionized water was applied. Data represent the msean of six replicate trays.

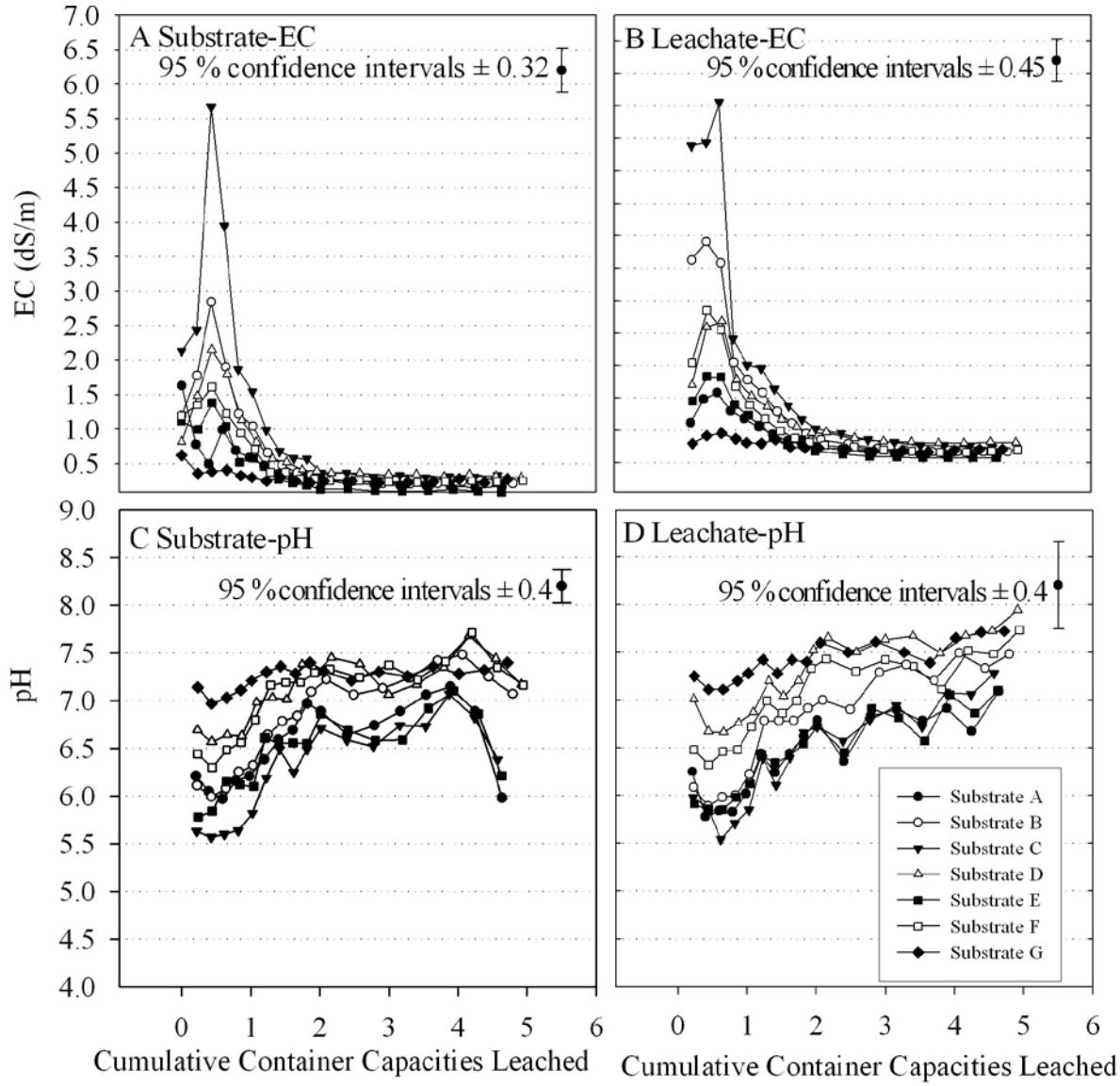

Figure 3-2. Substrate and leachate electrical conductivity (EC) and pH. Substrate-electrical conductivity (A), (B) leachate-EC, (C) substrate-pH and (D) leachate pH determined in samples collected from Commercial Substrate Experiment over 24 irrigations. Data represent the mean of four replicate trays. Commercial substrates A (100 % peat, 66N-33P-110K in mg of nutrient per L of substrate), B (80 % peat/20 % perlite, 61N-32P-122K), C (70 % peat/20 % perlite/10 % vermiculite, 136N-163P-326K), D (85 % peat/10 % perlite/5 % vermiculite, 82N-31P-86K), E (80 % peat/2 % perlite, 31N-25P-145K), F (60 % peat/40 % perlite, 41N-11P-68K) and G (70 % peat/30 % perlite, 0N-0P-0K) were irrigated with deionized water. Substrate G was a research substrate with no pre-plant fertilizer charge.

CHAPTER 4
EFFECT OF FERTILIZER CONCENTRATION AND APPLICATION VOLUME ON CORRECTING NUTRIENT-DEFICIENCY IN PETUNIA CUTTINGS

Introduction

Studies by Santos et al. (2008) showed that a wide range of nutrient concentration of water-soluble fertilizer is applied in commercial propagation of herbaceous annuals ranging from 0 up to 194 mg $N \cdot L^{-1}$ in a 4 week period. In plug production of annual bedding plants, pre-plant fertilizer is not expected to last more then 10 days. When substrates without pre-plant charge were used, nutrient solution should be applied as soon as germination is visible. Based on seedling growth and irrigation practices, nutrient concentration in solution can range from 25 to 150 mg $N \cdot L^{-1}$ (Styer and Koranski, 1997).

Common nutrient deficiencies in plants arise due to insufficient supply of N, P, and/or K. In carnation production, N deficiency appears as a yellowish color of the lower leaves, and with time the leaf sizes reduced, chlorosis increased, and flower production and growth can be adversely affected (Medina, 1992; Dole and Gibson, 2006). Phosphorus represents the energy source for plants. Lack of phosphorus results in delay in growth and maturity; overall the plants are stunted and seldom exhibit foliar symptoms such as dark green stems and leaves that often contain red or purple areas (Medina, 1992; Barker and Pilbeam, 2006). Mild phosphorus deficiency resulting from low P concentrations in applied fertilizer is used to produce compact seedling plugs (Huang et al., 2002). Potassium is needed to control water movement between cells. Potassium deficiency symptoms may appear first as dull grey-green older leaves. In severe cases, cholorosis and necrosis appear at the margins of leaves, along with reduced plant size (Medina, 1992; Barker and Pilbeam, 2006; Handreck and Black, 2008;). Nitrogen, P and K are required by plants in larger quantities, but all macro and micronutrients are important to plant

growth. A shortage of any of the these elements will result in less growth (Hewitt and Watson, 1980; Barker and Pilbeam, 2006). In petunias, iron deficiency often occurs when substrate-pH is above 6.5 (Argo and Fisher, 2002), and boron deficiency is also a common environmentally-induced problem when transpiration and nutrient uptake are reduced (Styer and Koranski, 1997).

Water-soluble nutrients leach readily from propagation substrate, regardless of the fertilizer form (Chapters 2 and 3). Conversely, N in the substrate solution in plug trays without plants was recharged when enough irrigation solution was applied to leach 1.5 CC (Chapter 2), at which point the substrate EC converged into the irrigation solution EC. Although leaching of nutrients from propagation substrate and correction of nutrient-deficiencies has been the subject of many studies, little research has been undertaken to correct deficient liners in plug trays. The objective was to evaluate plant growth response in nutrient-deficient petunia to a single irrigation with a fertilizer solution that varied in nutrient concentration (deionized water (DI water), 300, 600 and 1200 mg·L^{-1} N, each of the nutrients solutions had 5 mg·L^{-1} Fe) and volume applied (412.2, 824.4 and 1236.5 mL per tray).

Materials and Methods

The experiment was a randomized complete block in a factorial design consisting of 12 treatment combinations from four nutrient concentration levels ((deionized water (DI water), 300, 600 and 1200 mg N·L^{-1} N derived from 17N-2.2P-14.1K (with 75 % N as NH_4-N) and three volumes applied (412.2, 824.4 and 1236.5 mL). The treatments consisted of 51 x 52-count trays of Petunia liners. Three trays were used to determine initial fresh and dry weight of the shoots prior treatment application. The remaining 48 trays were divided in into four groups of 12 trays per nutrient level treatment. Within each nutrient level treatment trays were divided in three groups of four. Each group received a different volume of the nutrient solution. Each tray

received the treatment only once, followed by three irrigations over the ensuing 10 days with clear tap water.

Greenhouse Conditions

Propagation trays (52-count propagation trays with the vent holes covered) were filled with a 70% peat/30% perlite substrate containing dolomitic limestone, a wetting agent, but no other pre-plant nutrients (Sun Gro Horticulture Distribution Inc., Bellevue, WA), and cuttings of *Petunia* x *hybrida* 'Supertunia Royal Velvet' (InnovaPlant, Costa Rica) were planted on March 27th 2009. After planting, the liners were kept at 21°C and under mist with a frequency of 7s every 30 min, using deionized water and a complete micronutrient blend with 2 mg Fe·L^{-1}. The micronutrient blend consisted of 1.4% S, 2% Fe, 1% Mn, 1% Zn, 0.5% Cu, 0.5% B and 0.2% Mo (GreenCare Fertilizers, Inc., Chicago, IL). After 31 days, the liners showed signs of nutrient-deficiencies (nitrogen phosphorus and iron) and a nutrient solution with 100 mg N·L^{-1} derived from 17N-2.2P-14.1K (with 75% NH_4-N, GreenCare) and 2 mg Fe·L^{-1} from micronutrient blend was applied to reduce nutrient stress. This fertigation was followed by irrigations with tap water (EC = 0.4 dS·m^{-1}) as needed. On day 45, plants showed signs of severe nitrogen, phosphorus and iron nutrient-deficiency (yellow and purple color) and at this point, the substrate-EC was 0.26 dS·m^{-1}, substrate-pH was 7.1, and SPAD Chlorophyll Index was 29.

On day 45, four irrigation solutions were applied: deionized water (0 mg·L^{-1} N), and nutrient solutions at 300, 600 and 1200 mg N·L^{-1} derived from 17N-2.2P-14.1K. The micronutrient blend at 5 mg Fe·L^{-1} was added to each of the nutrient solutions (using the same fertilizer forms). The irrigation solutions had electrical conductivities of 0, 2.55, 5.1 and 10. 2 dS·m^{-1}. Each of these solutions was applied at three volumes (412.2, 824.4 and 1236.5 mL per propagation tray, which was equivalent to 0.57, 1.14, and 1.71 container capacity (CC) applied),

with 303, 722 and 1112.1 mL of leachate (or 0.4, 1 and 1.5 CC leached). The amount of N applied per tray was determined by multiplying the nutrient concentrations by the volume applied. Volume of irrigation solution applied was determined by multiplying the volume of irrigation solution collected in collection trays (15.2 x 38.1 cm) that passed though the stationary boom by 1.3 (1.3 was the correction factor from the collection tray surface area to the propagation tray (770 cm^2 (propagation tray area) divided by 579.12 cm^2 (collection tray area) = 1.3)). Volume of leachate was calculating by multiplying the volume of leachate from collection trays (placed underneath of propagation trays during irrigation) by 1.3 (the correction factor). The volume applied and leached was further divided by the CC and expressed as CC applied or leached.

Container capacity was determined by the same procedure as in Chapter 1 and equaled 722 mL per tray or 14 mL per cell. The substrate water content was determined 30 min before and 30 minutes after treatment application by dividing the weight of the trays by the CC minus the weight of tray empty, and equaled 74 % and 94 % of CC. The substrate water content was the same between the three application volumes. Treatments were applied to trays that moved on a conveyer belt through a stationary boom (Blackmore Co., Belleville, IL) with speeds of 12, 24 and 36 cm per second depending on the volume of the irrigation solution applied. Immediately after treatments the leaves were sprayed with deionized (DI) water to wash salts into the substrate and prevent phytotoxicity of foliage.

In the following weeks, tap water was applied three times when irrigation was needed (three, seven, and 10 days after treatment). Substrate solution samples were collected by plug press method in order to measure EC and pH (Scoggins et al., 2002). EC and pH were measured 30 min before, 30 min after, and 10 days after treatment application, using the same methods and

analytical techniques described in Chapter 3. SPAD Chlorophyll Index was measured for each replicate at 30 minutes and 10 days after treatment applications with a SPAD 502 meter (Minolta Camera Co., Spectrum Technologies, 12360 South East-Plainfield, IL) with four measurements per replicate tray, and each measurement was the average of five readings on the same plant but different leaves. To determine the fresh and dry weight, shoots were harvested and washed with DI water, fresh weight was measured, samples were dried in the oven at 70°C for 24 hours, and dry weight was determined. Fresh and dry weights were measured on plants from three replicates trays before treatment application and four trays per treatment at 10 days after treatment application. Dried tissue samples were analyzed for total nutrients (N, P, K and Fe) at Quality Analytical Laboratories (Panama City, FL.) using an inductively-coupled plasma (ICP) atomic emission spectrophotometry (Thermo-Jarrell Ash ICAP 61E; Franklin, Mass.) for analysis of all the nutrients except N. Nitrogen was measured using a Lachat QuikChem AE (Lachat Instruments; Loveland, Col.) at Quality Analytical Laboratories (Panama City, Fl.).

Data Analysis

Data were analyzed using the PROC GLM general linear model in SAS separately by measurement time, with a factorial design where effects were the nutrient concentration (four levels), application volume (three levels), and the concentration x volume interaction. Treatment means were separated using the Tukey's Studentized Range (HSD) test. The 95% pooled confidence intervals were determined for all nutrients levels and volumes applied. .

Results and Discussion

Substrate EC (Figure 4-1) was affected by the interaction between the concentration and volume of the irrigation solution applied ($P < 0.0001$) 30 min after treatment application. EC increased with increasing nutrient concentration and volume applied, except for DI water where

EC was a minimum of 0.1 $dS \cdot m^{-1}$ following 1.71 CC applied with no significance difference among the treatments.

In past experiments without plants, after leaching 1.5 CCCL, the substrate-EC converged to the irrigation solution EC (Chapters 2 and 3; Kerr and Hanan, 1985). However, the substrate-EC in this experiment did not reach the EC of the nutrient solution applied even at the highest application volume. For example, substrate-EC was 23 % (substrate-EC (2.55) divided by applied solution-EC), 36, and 54% of the 300 mg $N \cdot L^{-1}$ nutrient solution EC when 0.57, 1.14 and 1.71CC were applied. Similarly, substrate-EC represented 21, 43 and 63% of the 600 mg $N \cdot L^{-1}$ nutrient solution EC (5.1 $dS \cdot m^{-1}$), and 22, 41 and 52 % of the 1200 mg $N \cdot L^{-1}$ nutrient solution-EC (10.2 $dS \cdot m^{-1}$) with the corresponding volumes. The difference between substrate and nutrient solution EC levels was most likely because this experiment was run with 45-day-old petunia liners with well-developed root systems, where many large pores were filled by roots, thereby reducing the overall air-filled porosity of the substrate. Hoag and Price (1997), and Raviv and Lieth (2008) showed that roots mainly grow in large pores whereas smaller pores constrict root development and very small pores contain the immobile fraction of substrate solution and adsorbed nutrients. Also some of the irrigation solution may have been lost through the space between the substrate and tray walls (preferred pathways), with less effect on the substrate solution. In addition, the solution was surface-applied to the foliage and then washed down into the substrate. Some solution may have remained on lower leaves.

By 10 days after treatment applications, the nutrient concentration and volumes applied no longer affected the substrate-EC ($P = 0.1181$). Substrate-EC ranged between 0.4 and 0.5 $dS \cdot m^{-1}$, which was close to the tap water EC (EC = 0.4 $dS \cdot m^{-1}$) that was applied three times during the 10 days after treatment application. Nutrients may have been taken up by plants, or partially

leached by the tap water irrigations although care was taken to minimize leaching during tap water irrigations.

The nutrient concentration and volume applied affected the substrate-pH ($P < 0.0001$) 30 minutes after treatment application (Figure 4-1 B). Substrate-pH increased following DI water treatments, remained the same (7.3) for 300 mg $N \cdot L^{-1}$ nutrient solution with all three volumes, and decreased for 600 and 1200 mg $N \cdot L^{-1}$ nutrient solutions with increase in volume with no significant difference between treatments. These results are consistent with results reported by Marc van Iersel (1999) who reported higher pH values when pansies were sub-irrigated with low nutrient concentrations. All these pH values are above the recommended level of 5.4 to 6.6 (Argo and Fisher, 2002).

The pH increased at day 10 for all treatments regardless of the nutrient concentration and volume applied. The highest pH was determined for treatments with deionized water applied at 1.71 CC and 300 mg $N \cdot L^{-1}$ applied at 0.57 CC. Overall pH was above the pH recommended range mentioned above with no significant difference between treatments.

Fresh and dry weights (Figure 4-2 B and C) were affected by the interaction of concentration and volume of the nutrient solution applied ($P < 0.0001$). Treatments with DI water had the lowest fresh and dry weight (0.8 and 0.09 g per plant respectively) and decreased with increased in volume applied with no significant difference among treatments. Plants treated with DI water looked very deficient, and growth was limited. Fresh and dry weight increased with increase of concentration and volume applied. Treatments at 600 and 1200 mg $N \cdot L^{-1}$ and 1.71 CC applied had the same fresh weight (2.1 g per plant) and dry weight (0.14 g per plant). I observed that 1 day after treatment, all plants that received 600 and 1200 mg $N \cdot L^{-1}$ were wilted although the substrate was wet, presumably because of the high osmotic potential of the substrate

solution. The EC values 30 minutes after treatment application were much higher than the recommended range for same of the treatments. For example, 600 mg $N \cdot L^{-1}$ applied at 1.14 and 1.71 CC and for 1200 mg $N \cdot L^{-1}$ ranged from 2.2 to 5 3 $dS \cdot m^{-1}$. In plug production, the recommended range for EC is between 0.75 and 2 $dS \cdot m^{-1}$ depending on the growth stage and species (Styer and Koranski, 1997).

The single irrigation treatment was sufficient to increase shoot N to recommended concentrations at 600 and 1200 mg $N \cdot L^{-1}$, except at the lowest application volume, but was insufficient to increase the P, K, Fe level concentrations in the shoot to the recommended level ranges. Nutrients level concentrations (N, P and K) in plant tissue (Figure 4-3) were affected by the interaction of the concentration and volume of the irrigation solution ($P < 0.0001$). These levels are generally lower for P, K, and Fe than recommended nutrient level concentrations in plant tissue (Mills and Jones Jr., 1996) of 3.85 to 7.60 % N, 0.47 to 0.93% P, and 3.13 to 6.65% K and 84 to 168 mg $Fe \cdot Kg^{-1}$ for petunia. However, the lower P, K, and Fe levels concentrations in this experiment may be partly explained by a difference in cultivars sampled, and also because our sample represented the entire above-substrate stems and shoots rather than just recently mature leaves.

Nutrient uptake into the shoot (Figure 4-4) was calculated by subtracting the initial shoot nutrient levels concentrations ($mg \cdot g^{-1}$ times grams of dry weight) from the final shoot nutrient level concentration. Uptake was affected by the interaction between concentration and volume applied for N, P, and K ($P < 0.0001$), and main effects only for Fe ($P < 0.0001$ for concentration, and $P = 0.0003$ for volume applied). When DI water was applied, the nutrient uptake was negative or close to zero for all volumes applied. Negative uptake in the DI treatment (-0.35 to -0.58 mg N per shoot with increasing DI water volume applied) may have represented movement

of nutrients from the shoot into the roots, however root nutrient levels concentrations and dry weight were not measured. Other explanation for the decreased in N may be the movement of nutrients out of roots. Overall nitrogen uptake increased with increased in mg of N applied per tray with no significant difference between treatments. When 600 mg $N \cdot L^{-1}$ were applied, the N uptake increased approximately 10 times compared with the N uptake when 300 mg $N \cdot L^{-1}$ nutrient solution were applied at 0.4 CC were leached (N uptake with 600 mg $N \cdot L^{-1}$ was divided by the nutrient uptake from treatment with 300 $mg \cdot L^{-1}$ N). There was an increased in N uptake when 1200 mg $N \cdot L^{-1}$ was applied compared with 600 mg $N \cdot L^{-1}$ nutrient solution when the same volume was leached, but the increase was smaller (two times). The N uptake varied not only with the concentration of the nutrient solution but also with increase in volume. Phosphorus did not changed when DI water was applied, but increased with increase in nutrient concentration and volume applied. Potassium had similar trends when compared with N uptake. Fe uptake decreased with increased in volume of DI water applied and increased with increase in nutrient concentration and volume applied. However a single irrigation is not enough to bring the nutrients levels concentrations up to the recommended range.

Conclusions

These results have implications on Best Management Practices. When well-rooted plugs or liners are nutrient-deficient, more than one fertilizer application with 1.71 CC applied was needed to recharge the nutrients in substrates. The same growth response in this study was obtained with low nutrient concentrations applied at high volumes or high nutrient concentration applied at low volumes. In other words, it was the mg of nutrient in root zone that is most important for plant uptake, which represented the combination of applied volume and concentration. Very high concentrations of nutrients (for example 600 or 1200 $mg \cdot L^{-1}$ N) may

induce phytotoxicity on foliage, and also cause an excessive increase in substrate-EC. Repeated applications of a lower concentration (for example, 300 $mg \cdot L^{-1}$ N) with high application volume may, therefore, cause the least plant stress to correct severe deficiencies.

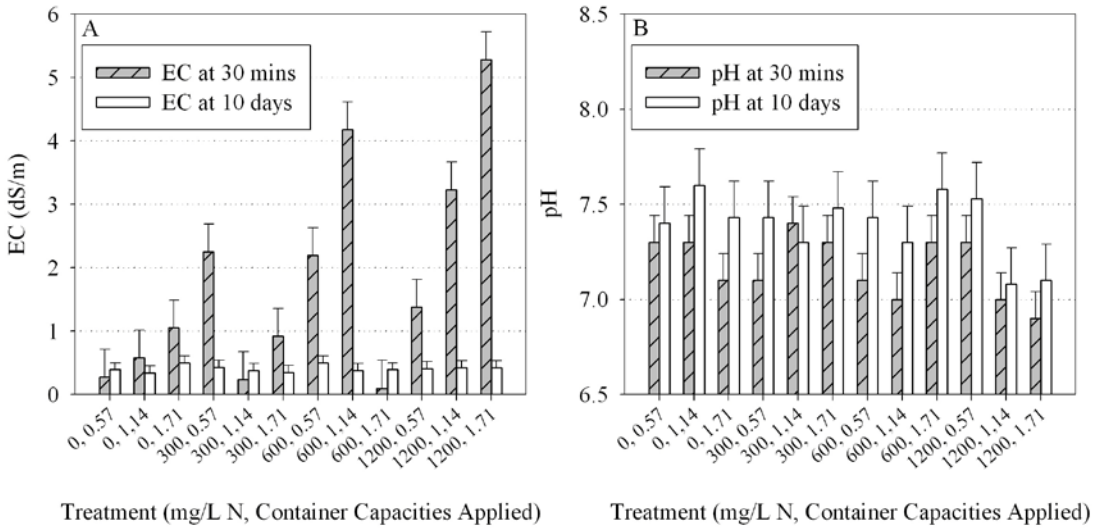

Figure 4-1. Substrate electrical conductivity (EC) and pH. Substrate-electrical conductivity (A), and (B) Substrate-pH were measured 30 minutes and 10 days after treatments application. Four nutrient solutions (with N at 0, 300, 600 and 1200 $mg \cdot L^{-1}$) were applied at three volumes (0.57, 1.14 and 1.71 container capacities). Data represent the mean of four replicate trays ± 95 % confidence intervals.

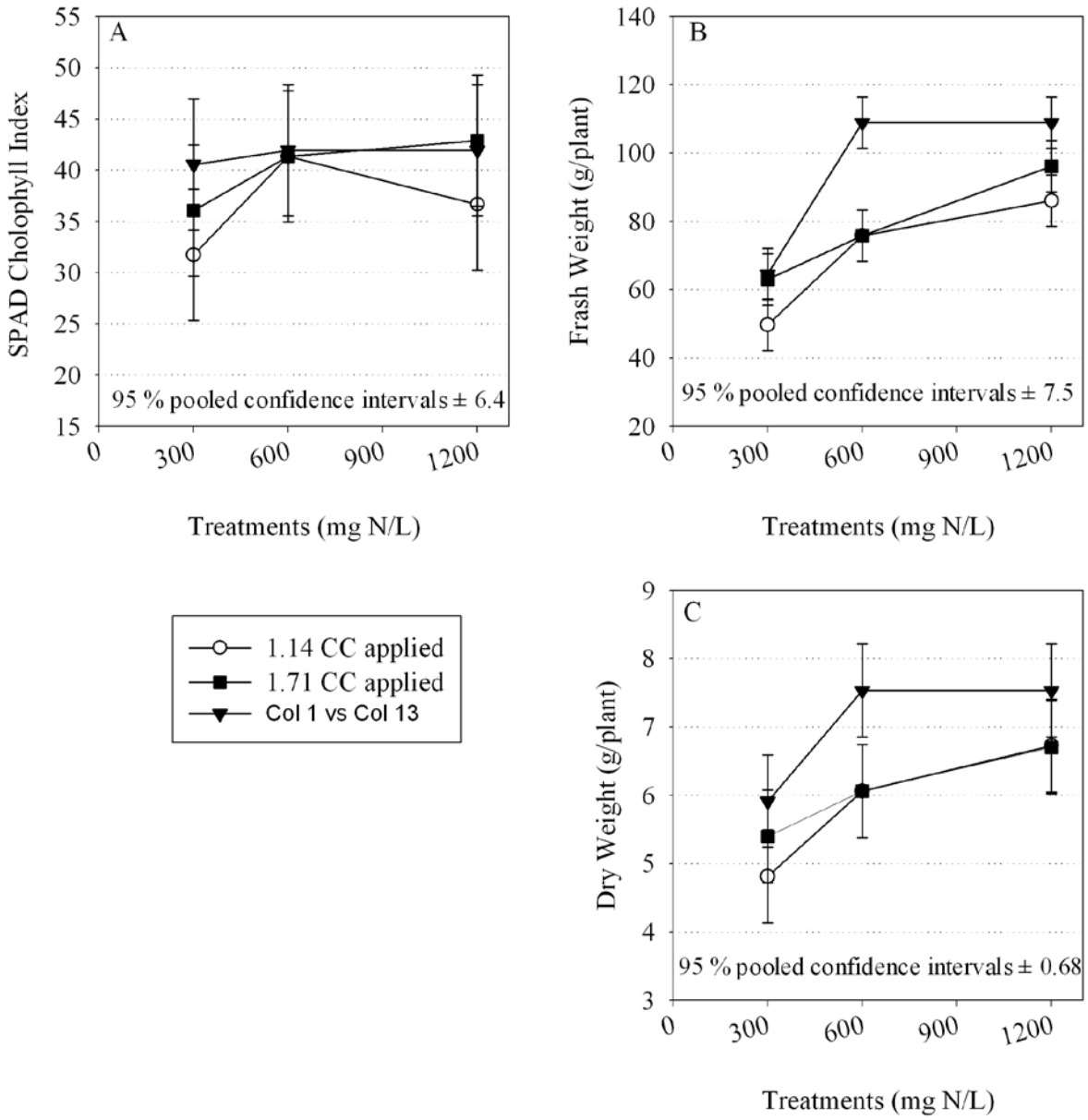

Figure 4- 2. Petunia growth response to different nutrient concentration solutions. SPAD Chlorophyll Index (A), fresh (B) and dry weight (C) 10 days after treatment application. Different nutrient concentrations 0, 300, 600, 1200 mg $N \cdot L^{-1}$) were applied at three volumes (0.57, 1.14 and 1.71 container capacities (CC)). Each point is the average of four replicate trays ± 95 % pooled confidence intervals.

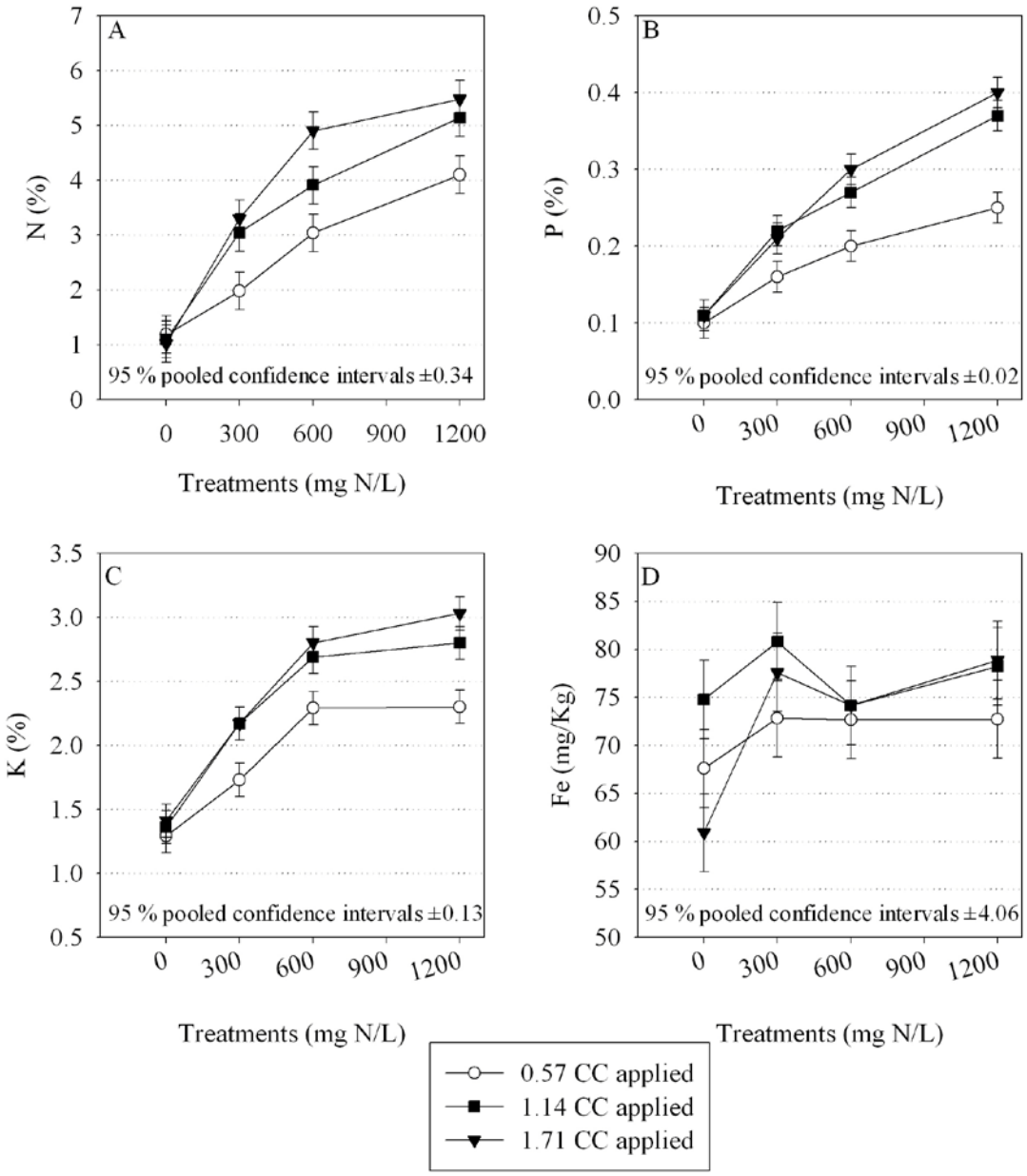

Figure 4-3. Nutrient concentrations (%) in tissue. Nitrogen (A), phosphorus (B), potassium (C) and iron (D) concentrations in tissue when different nutrient concentrations (0, 300, 600 and 1200 mg·L^{-1} N) were applied at three volumes (0.57, 1.14 and 1.71 container capacities (CC). Data represent the mean of four replicates per treatment ± 95 % pooled confidence intervals.

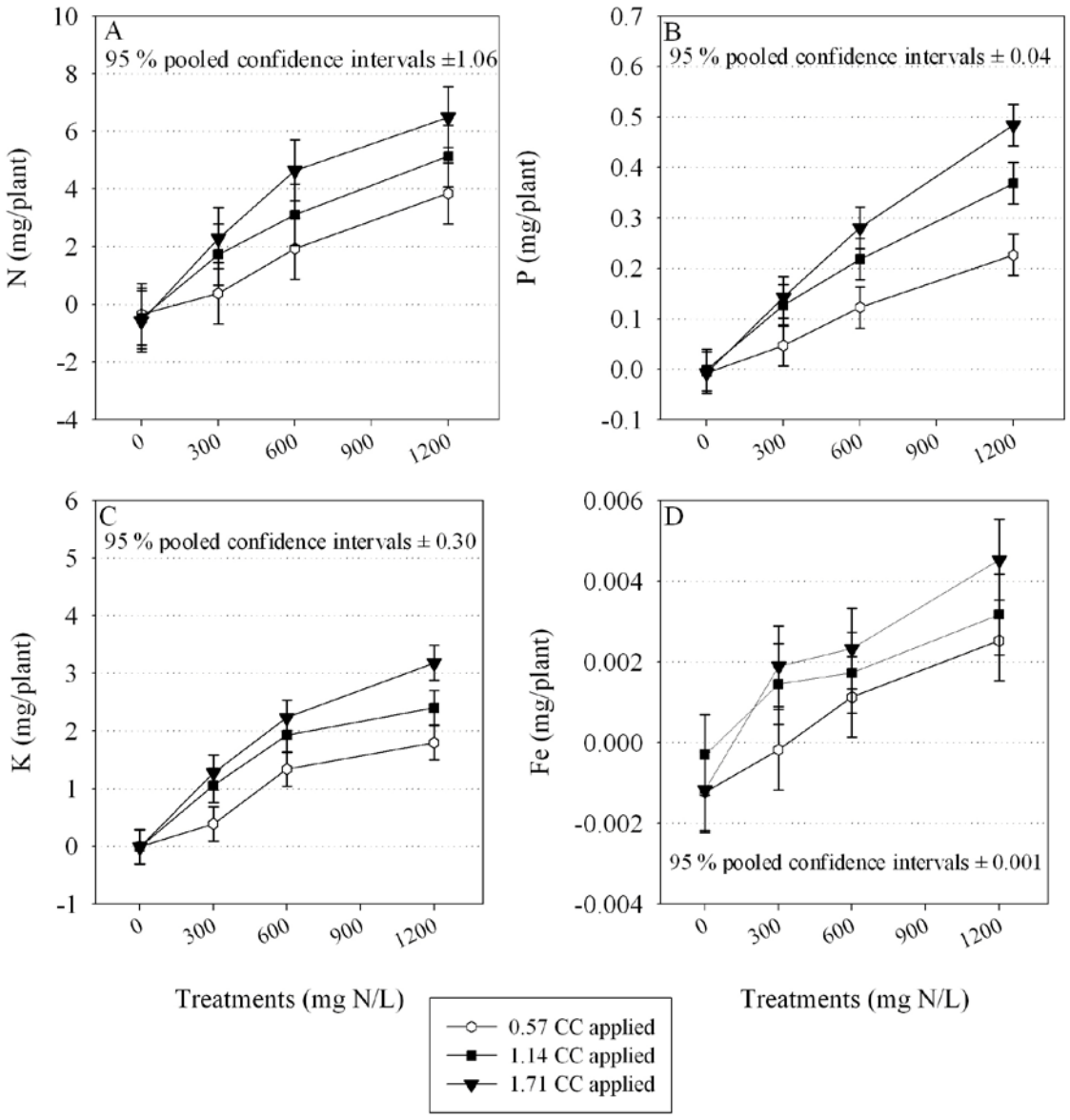

Figure 4-4. Nutrient uptake (mg/plant). Nitrogen (A), phosphorus (B), potassium (C) and iron (D) concentrations when different nutrient concentrations (0, 300, 600 and 1200 $mg \cdot L^{-1}$ N) were applied at three volumes (0.57, 1.14 and 1.71 container capacities (CC)). Initial levels of N, P, K and Fe were subtracted from the final levels to obtain only the nutrients absorbed by the plant due to the treatments. Data represent the mean of four replicates per treatment ± 95 % pooled confidence intervals.

CHAPTER 5
CONCLUSIONS

This thesis provided an in-depth evaluation of how nutrients are leached or replaced in greenhouse propagation substrates. Experiments were conducted that varied the nutrient concentration applied solution (DI or nutrient solutions), substrate types (mainly peat/perlite based, but including commercial substrates that included vermiculite or were peat only), and incorporated fertilizers (water soluble fertilizers with a range in nitrate:ammonium ratio, or a controlled-release fertilizer), in systems with or without plants.

The nutrient leaching was consistent between the water-soluble fertilizers and substrates tested, whereby substrate-EC increased as nutrients were solubilized during the first 0.5 CC leached, followed by a gradual convergence of the substrate-EC and applied solution EC. By the time 1.5 CC were leached in substrates without plants, substrate and applied EC were similar. When petunia liners that had fully developed root systems, which would reduce the pore space, were used, the substrate-EC was still lower than the applied solution EC after leaching 1.7 CC.

Overall, our results have the following implications for Best Management Practices:

1. Water soluble fertilizers leach rapidly, regardless of the nitrate:ammonium ratio, because of the low cation and anion exchange capacity of propagation substrates.

2. Reducing the amount of water applied during misting and subsequent irrigation is an important goal to maintain the pre-plant fertilizer in the substrate and thereby reduce runoff. Leaching should be matched to the evapotranspiration needs of cuttings, and therefore controlling mist with a climate model and sensors would be more effective than misting based on a time-clock. Fog-type control of humidity and cutting hydration would be very desirable to reduce nutrient leaching.

3. Applying a high rate of water-soluble fertilizer incorporated in the substrate is not justified in cutting propagation because plants start as unrooted cuttings, and therefore do not take up nutrients efficiently until they have roots. Growers should be especially careful to minimize leaching when fertilizer is incorporated. Nutrients should be recharged with a fertigation solution applied after the root system is formed and developed and the trays are removed from mist.

4. An alternative to water-soluble fertilizer is controlled-release fertilizer, which had a more gradual leaching. Leaching could be reduced with this technology if certain technical issues could be overcome (such as even distribution between cells and a 4- to 6-week release period). Given currently-available fertilizer products, however, controlled release fertilizers are only suitable for propagation of larger plant material (particularly woody plants) grown for a longer period than a 6-week crop cycle.

5. When well-rooted plugs or liners are nutrient-deficient, more than one fertilizer application with 1.5 CC leached may be needed to recharge the nutrients in substrates. The same growth response could be obtained with low nutrient concentrations applied at high volumes or high nutrient concentrations applied at low volumes. In other words, it is mg of nutrient per mg of substrate that is most important for plant uptake, which is the combination of applied volume and concentration. Very high concentrations of nutrients (for example 600 or 1200 $mg \cdot L^{-1}$ N) may induce phytotoxicity on foliage, and also cause an excessive increase in substrate-EC. Repeated applications of a lower concentration (for example, 300 $mg \cdot L^{-1}$ N) with high application volume may therefore cause the least plant stress to correct severe deficiencies of petunia.

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BIOGRAPHICAL SKETCH

Angelica Cretu was born in Oltenita, Romania to Dumitru Cretu and Valeria Cretu. She grew up in South of Romania close to the Danube River. She graduated from University of Agricultural Sciences and Veterinary Medicine Bucharest Romania with a B.S. in agronomy in July 1999. Following graduation, she was employed by DecoFlora Inc. Bucharest, Romania, as an agronomist from July 2000 until May 2003. From May 2003 until October 2006 she worked for Hemann Engelmann Greenhouses, FL, as a grower. In January 2007 she enrolled in graduate studies at the University of Florida. Currently, Angelica completed the requirements for the Master of Science degree in the environmental horticulture, under the direction of Dr. Paul Fisher.