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Automated ebb-and-flow subirrigation for citrus liners production. I. Plant growth

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ABSTRACT

Ebb-and-flow subirrigation is a closed system that applies water to the bottom of the containers, reducing water and nutrient losses due to recirculation of fertilizer solution (FS). The technology can improve plant growth and eliminate the improper disposal of salts into the environment. Subirrigation is widely used in the ornamental industry, and sensor-based ebb-and-flow benches can be used by the citrus nursery industry. There is a need for establishing water and fertilizer guidelines to produce citrus rootstocks. The objectives of this study were: 1) design and build an ebb-and-flow subirrigation equipment, 2) automate the system operation using soil moisture sensors, 3) evaluate the system performance on plant growth, and 4) determine the water and fertilizer guidelines to produce Rangpur lime (*Citrus* × *limonia*) liners in 56-cm^3 cone-shaped containers. The treatments were four volumetric water content (VWC) to trigger subirrigation (0.12, 0.24, 0.36 and 0.48 m^3 m^{-3}), three FS concentrations (25%, 50% and 75% of the fertilizer recommendation) and a control (nursery manual overhead irrigation using breaker nozzles), arranged in a completely randomized 4 × 3 + 1 factorial plus design, with three replications. The system was automated by 39 capacitance sensors connected to a data logger, multiplexer and relay drivers, which controlled independent submersible pumps. Subirrigation was turned on when VWC dropped below the set thresholds. Sensors effectively monitored the substrate moisture and controlled subirrigation. Treatments with highest VWC had higher substrate moisture and number of irrigations over time ($p < 0.0001$). The volume of water applied doubled from treatments 0.12–0.48 m^3 m^{-3} ($p < 0.0001$). Subirrigation increased shoot height, stem diameter, dry weight, leaf area, physiological parameters (leaf intracellular concentration of CO_2, transpiration, stomatal conductance, and net photosynthesis), and water use efficiency in response to increase in VWC and FS ($p < 0.0001$). Subirrigation shortened the crop cycle in 30 days, anticipating the liners transplant for grafting, allowing another cultivation cycle in the nursery during the year. VWC of 0.48 m^3 m^{-3} and FS concentration of 50% of the recommended value for overhead irrigation are indicated for Rangpur lime liner production in 56-cm^3 containers.

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1. Introduction

Citrus trees are produced in closed screen houses to shorten the production time, reduce juvenility and anticipate stable fruit production, allow propagation of pest- and disease free plants and uniformize plant size. Irrigation is usually performed manually by using breaker nozzles or drilled PVC pipe wands on garden hoses and automatically using spray bars. Manual overhead systems are characterized by minimal control of water delivery, often leading to excessive or deficit irrigation, reduced irrigation efficiency, and increased production costs (Salvador et al., 2016). Part of the leachate reaches the soil with potential for salinization and environmental contamination due to the high amount of salts dissolved in the solution (Salvador et al., 2016). Additionally, the “umbrella effect” (i.e., water redirection by leaves) reduces the water and nutrient uptake causing significant losses. There is a lack of environmental-friendly water management strategies on citrus liners production (Salvador et al., 2014). A more efficient irrigation system is needed to decrease those impacts and enhance plant growth.

Subirrigation applies water to the bottom of pots, wetting the substrate by capillary action (Ferrarezi et al., 2015a). Subirrigation is widely used in the ornamental industry (Ferrarezi et al., 2015b).

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Table 1
Benefits of subirrigation systems to plants, production systems, environment and operation.

Benefit to plants	Benefits to production system	Benefits to environment	Benefits to operation
Higher plant quality and uniformity (Biernbaum, 1990; Giacomelli and Ting, 1999)	Effective weed control (Rouphael et al., 2008; Wilen et al., 1999)	Elimination of water and fertilizer losses due to zero runoff (Bumgarner et al., 2008; Strong et al., 1997; van Iersel and Kang, 2002; Zheng et al., 2004)	Possibility of automation (Bauerle, 1990; Ferrarezi et al., 2015a., 2015b; Treder et al., 1997)
Shortened plant cycle (Barreto, 2011; Pennisi et al., 2005)	Higher soil moisture than maintained by hand watering (Hoffman et al., 1996)	Reduction of the dispersion of chemical contaminants (Million et al., 1999)	High irrigation uniformity (Santamaria et al., 2003)
Increased production per unit area (Rouphael et al., 2006)	Reduction in pathogen spreading due to the avoidance of foliar wetting (Rouphael et al., 2006; Zheng et al., 2004)	Reduction in the amount of water applied (James and van Iersel, 2001a; van Iersel and Kang, 2002), which would be 25% less than the amount applied by drip irrigation (Martinetti et al., 2008)	Less water use per bench area (ten times less when compared to overhead system) (Klock-Moore and Broschat, 2000)
Possibility of drought stress imposition to condition plants for shipping, marketing, and planting (Ferrarezi et al., 2015a; van Iersel and Nemali, 2004)	Possibility of pesticide (van Iersel et al., 2001), plant growth promoter (Rouphael et al., 2006), and regulator application (Hwang et al., 2010; Million et al., 1999; Million et al., 2002)	Reduction in the environmental pollution and higher fertigation efficiency (91%) when compared to drip irrigation (79%) (Martinetti et al., 2008; Majsztrik et al., 2011)	Low required operating pressures, resulting in less pumping power requirements (Stanley and Harbaugh, 2004) and energy savings (Martínez et al., 2010)
Promote the production of compact plants (James and van Iersel, 2001b)	Adequate and uniform supply (Laviola et al., 2007) and reduced amount of fertilizer use (Bauerle, 1990)	Little to no NO_3—N losses due to fertilizer solution recirculation (Klock-Moore and Broschat, 2000)	Simple and flexible system engineering (Elliott, 1990)
	Reduced substrate compaction over time (Biernbaum, 1990)	Increased fertilizer (Schmal et al., 2011) and water use efficiency (Morvant et al., 1997)	
	Flexibility in pot sizing and spacing (Rouphael et al., 2008)		

The technology has several benefits related to plants, production systems, environment and operation compared to other irrigation systems used in protected plant production (Table 1). Most growers and researchers can be quick to note that water and fertilizer savings are significant, but agree that the savings do not contribute significantly to pay off the system (Biernbaum, 1990). Labor savings is the most important reason to recommend the system since the lower labor demand for irrigation is a key benefit (Uva et al., 1998), especially in high value crops where the cost of labor is more representative (Uva et al., 2001). The increased crop uniformity also helps with shipping and keeps losses down to a minimum (Biernbaum, 1990).

On the other hand, this system could have some limitations regarding its commercial use, such as potential for salt accumulation in the upper layer of the substrate relative to the bottom in contact with water (Cox, 2001; Dole et al., 1994; Nemali and van Iersel, 2004b; Richards and Reed, 2004; Rouphael et al., 2006); high initial deployment and maintenance cost (Elliott, 1990; Uva et al., 1998); risk of pathogen spread, especially those propagated by water (van Der Gaag et al., 2001); lack of adequate water and nutritional management for different substrates (Caron et al., 2005); and high variation in the soil moisture over time (Ferrarezi et al., 2015a).

The subirrigation equipment are classified as ebb-and-flow benches, flood-floor, trough-tray, wick system, mobile or Dutch trays, and capillary mat (Ferrarezi et al., 2015b), and are commonly chose based on greenhouse space availability, cost and target crop. Subirrigation can be used to produce citrus trees (Salvador et al., 2014). Giuliani et al. (2014) tested subirrigation for citrus liner germination but with poor results due to the lack of proper water and nutrient management. Similar results were found by Teixeira et al. (2010) which grown several citrus rootstocks but using a floating irrigation system. Information related to subirrigation application on citrus nursery production using ebb-and-flow benches is not available. One of the main limitations is the lack of commercial equipment availability. There is a need to develop an equipment following design criteria such as ergonomics, functionality, and manufacturing material resistant to severe environmental conditions such as constant sunlight exposition and high temperatures (Ribeiro et al., 2014). Previous research has determined the best equipment and stablished an innovative design (Ferreira Filho et al., 2011). A prototype was built and the hydraulic parameters were studied (Ribeiro, 2013). However, the system was never tested on citrus nursery commercial production.

Subirrigation control is usually based on timers, without monitoring plant water requirements or substrate volumetric water content (VWC) for optimal plant growth, often resulting in excessive water application and inefficient operation (Ferrarezi et al., 2015a). A real-time technique to estimate the substrate moisture and apply water according to plant needs is imperative for commercial subirrigation application. Capacitance sensors can be used to both monitor substrate water content and to control subirrigation based on plant water use, thus applying water as needed, optimizing plant production, and increasing water use efficiency (WUE). Capacitance sensor operation, mode of action and technical characteristics such as response to temperature and conductivity variation are well described by Bogena et al. (2007). Sensors were previously used in subirrigation in hibiscus (*Hibiscus acetosella*) and salvia (*Salvia splendens*) (Ferrarezi et al., 2015b) and in zonal geranium (*Pelargonium* × *hortorum*) (Gent and McAvoy, 2011) but never in citrus rootstock liners.

Specific water and fertilizer guidelines are needed for commercial production of Rangpur lime (*Citrus* × *limonia*) liners production using subirrigation. Current management practices are based on the reduction of the nutrient concentrations from the fertilizer guidelines because salts are not leached out and can accumulate in the root zone (Ferrarezi et al., 2015b). The recommendations used in other irrigation systems are not suitable for subirrigation, and specific guidelines are required for commercial utilization.

The objectives of this study were 1) design and build an automated ebb-and-flow subirrigation bench, 2) automate the system operation using soil moisture sensors, 3) evaluate the system performance on plant growth, and 4) determine the water and fertilizer guidelines to produce Rangpur lime liners in 56-cm^3 cone-shaped containers.