Controlled-release Fertilizer during Cutting Propagation Affects Growth and Tissue Nutrient Concentrations of Rooted Cuttings of Annual Bedding Plants

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Additional index words. liners, macronutrient, micronutrient, vegetative, water-soluble fertilizer

Abstract. Our objectives were to quantify the effects of controlled-release fertilizer (CRF) on the growth, morphology, and tissue nutrient concentration of annual bedding plants during propagation. Unrooted cuttings of *Angelonia angustifolia* ‘AngelFace White’ and ‘Sundancer Pink’, *Impatiens hawkeri* ‘Celebrette Apricot’ and ‘Celebrette Rose Hot’, *Nemesia fruticans* ‘Bluebird’ and ‘Raspberry Sachet’, *Pelargonium × hortorum* ‘Savannah Red’, and *Petunia × hybrida* ‘Cascadia Marshmallow Pink’ and ‘Suncatcher Yellow’ were received from a commercial propagator. Cuttings were immediately stuck individually in cells containing soilless substrate supplemented with 0, 3, 6, 12, or 24 g·L⁻¹ CRF (Osmocote Plus 15–3.9–10 3–4 month) and placed under clear mist water or cuttings were stuck in substrate containing no CRF and fertilized with water-soluble fertilizer beginning immediately after placing cuttings into propagation. Shoot dry mass of cuttings grown in substrates containing up to 12 or 24 g·L⁻¹ CRF increased by up to 150% for some taxa compared with unfertilized cuttings. Incorporating CRFs into propagation substrates increased the concentration of nitrogen (N), phosphorus (P), and potassium (K) in tissues by up to 103%, 42%, and 137%, respectively, compared with unfertilized cuttings. Additionally, tissue nutrient concentrations for cuttings fertilized with 6 g·L⁻¹ CRF or greater were similar to cuttings receiving water-soluble fertilizer (WSF). When the impact of CRF on growth and nutrient concentrations are taken together, our results indicate that CRF is a fertilization application technology that holds promise for use during propagation of herbaceous stem-tip cuttings.

Young plants propagated from seed (plugs) or stem-tip cuttings (liners) are commonly used in herbaceous ornamental annual bedding plant production and propagative material for this use is currently valued at over \$159 million (U.S. Department of Agriculture, 2012). Unrooted cuttings received in the United States generally have tissue nutrient concentrations

within published, recommended ranges on receipt (Gibson et al., 2007; Santos et al., 2011a). However, during the propagation phase of herbaceous stem-tip cuttings, the concentration declines resulting from leaching of nutrients and the dilution effect, whereas mineral nutrient content in tissues decline from leaching (Blazich, 1988; Svenson and Davies, 1995). As a result, the mineral nutrient content and concentrations of cuttings must be replenished during propagation, and this is frequently accomplished by providing mineral nutrients through application of WSF.

A survey of greenhouse producers of liners conducted by Santos et al. (2008) reported large variation among fertilization application practices in propagation facilities. It is common practice for producers to begin providing WSF during the first week of cutting propagation, either through mist application or substrate fertigation, increasing fertilizer application concentration as propagation proceeds. As propagation proceeds from callusing (Stage 2) to toning (Stage 4), fertilizer application concentration increases from 0 to 200 mg·L⁻¹ of N applied through mist or 0 to 400 mg·L⁻¹ applied with a hose. Santos et al. (2008) also reported that up to 46.9 L of

leachate/m² of bench space was leached from the root zone during a typical 4-week production cycle for rooted cuttings. Furthermore, 23%, 34%, and 28% of N, P, and K applied, respectively, were leached during propagation in eight different commercial greenhouses (Santos et al., 2008).

CRFs are polymer-enclosed fertilizers that release nutrients based on the temperature and moisture status of the substrate (Nelson, 2012; Sonneveld and Voogt, 2009). Additionally, CRFs have several distinct advantages compared with traditional WSF, including the potential to reduce levels of mineral nutrient leaching. Greenhouse producers of high-quality rooted cuttings aim to provide a sufficient supply of mineral nutrients and an environment conducive to nutrient uptake and assimilation to minimize production time. However, it is also of interest to limit excessive nutrient application and leaching in the propagation environment to minimize loss of fertilizer and runoff. Therefore, the same advantages that CRFs may confer for containerized crop production are also desirable in cutting propagation. Our objectives in this study were to quantify the effectiveness of CRFs during propagation of herbaceous stem-tip cuttings compared with traditional WSF.

Materials and Methods

Expt. 1. On 18 Jan. 2012, ≈100 cuttings of *Angelonia angustifolia* ‘AngelFace White’ and ‘Sundancer Pink’, *Nemesia fruticans* ‘Bluebird’ and ‘Raspberry Sachet’, and *Petunia × hybrida* ‘Cascadia Marshmallow Pink’ were received at Purdue University, West Lafayette, IN (lat. 40° N). Cuttings were placed in 105-cell propagation trays (28-mL individual cell volume; T.O. Plastics, Inc., Clearwater, MN) filled with a propagation substrate composed of (v/v) three parts soilless substrate (Fafard 1P; Conrad Fafard, Inc., Agawam, MA) and one part coarse perlite (Strong-Lite Coarse Perlite; Sun Gro Horticulture, Bellevue, WA) containing 0, 3, 6, 12, or 24 g·L⁻¹ CRF (Osmocote Plus 15N–3.9P–10K 3–4 month; Everris NA, Inc., Dublin, OH). Cuttings were sprayed to runoff with a solution containing 300 mg·L⁻¹ non-ionic surfactant (CapSil; Aquatrols, Paulsboro, NJ) so that water would not accumulate on the plant foliage surface.

Cuttings in propagation substrate containing 0 to 24 g·L⁻¹ CRF then were misted with tap water supplemented with 93% sulfuric acid (Brenntag, Reading, PA) at 0.08 mL·L⁻¹ to reduce total alkalinity concentration to 100 mg·L⁻¹ and to maintain a water pH to a range of 5.8 to 6.2. An additional group of cuttings was placed in substrate containing no CRF and were misted with acidified tap water supplemented with a complete WSF (Jack’s LX 16N–0.9P–12.3K Plug Formula for High Alkalinity Water; J.R. Peters, Inc., Allentown, PA) and micronutrient supplement (Compound 111; Everris NA, Inc.) providing (in mg·L⁻¹) with each misting event: 60 N, 6 P, 47 K, 11 calcium (Ca), 6 magnesium (Mg), 0.3 boron (B), 0.1 copper (Cu), 1.5 iron (Fe),

Received for publication 2 May 2013. Accepted for publication 4 Dec. 2013.

We gratefully acknowledge Tyler Mason, Rob Eddy, and Dan Hahn for greenhouse assistance, funding from growers providing support for Purdue University floriculture research, and support from the Purdue Agricultural Experiment Station. We thank Ball Horticultural Co. for plant material, Conrad Fafard, Inc. for substrate, Everris for the controlled-release fertilizer and tissue analyses, Ludvig Svensson for shade cloth, J.R. Peters, Inc. for water-soluble fertilizer, and the Indiana Flower Growers Association and Fred C. Gloeckner Foundation, Inc. for support.

The use of trade names in this publication does not imply endorsement by Purdue University of products named nor criticism of similar ones not mentioned.

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Fig. 1. (A–O) Stem length, stem caliper, shoot and root dry mass, and root:shoot dry mass ratio of *Angelonia* 'AngelFace White' and 'Sundancer Pink', *Nemesia* 'Bluebird' and 'Raspberry Sachet', and *Petunia* 'Cascadia Marshmallow pink' cuttings 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of 14 cuttings, and error bars represent SEM of the mean. Different letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

0.4 manganese (Mn), 0.09 molybdenum (Mo), and 0.21 zinc (Zn).

Ten days after the placement of cuttings in propagation treatments, the use of mist was discontinued. Cuttings grown in substrates containing CRFs were irrigated with unfertilized water, whereas cuttings grown with WSF were hand-irrigated with acidified water supplemented with a combination of two WSFs (3:1 mixture of 15N–2.2P–12.5K and 21N–2.2P–16.6K, respectively; Everris NA, Inc.) to provide the following (in $\text{mg}\cdot\text{L}^{-1}$): 200 N, 26 P, 163 K, 50 Ca, 20 Mg, 1.0 Fe, 0.5 Mn and Zn, 0.2 Cu and B, and 0.1 Mo.

All cuttings were placed in a glass-glazed greenhouse under a 16-h photoperiod with air and substrate temperature set points of $23 \pm 1^\circ\text{C}$ and a daily light integral maintained at $\approx 5 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for callusing and ≈ 10 to $12 \text{ mol}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ for rooting. Resistance-based sensors (External Temperature Sensor; Spectrum Technologies, Inc.) recorded air and substrate temperatures every 30 s and averages were logged every 15 min by a data logger (Watchdog 2800 Weather Station; Spectrum Technologies, Inc.). Two amplified quantum sensors (SQ-212; Apogee Instruments, Inc., Logan, UT) measured photosynthetic photon flux every 30 s under each

lighting treatment, and the average of each sensor was logged every 15 min by a data logger (Watchdog 2800 Weather Station; Spectrum Technologies, Inc.).

Data were collected after 28 d of propagation. Cuttings were removed from propagation trays and substrate was gently rinsed off the roots. Stem caliper above the lowest leaf and stem length from the base of the cutting to the apical meristem were measured with a digital caliper (digiMax; Wiha, Schonach, Germany). Roots and leaves were excised from the stem and were dried separately in an oven at 70°C for 3 d, after which shoot (SDM) and root dry mass (RDM) were recorded.

Dried shoot tissue of samples for each 14-cell propagation strip was combined for tissue analyses. Determination of Kjeldahl nitrogen for all tissue samples began with standard digestion in concentrated sulfuric acid at 360 °C for ≈ 1.5 h using a Tecator 40 block digester. The resultant ammonium fraction was measured with a Lachat Quik-Chem 8500 flow-injection analyzer using a buffered salicylate–hypochlorite solution for color development. Determination of elemental species (Ca, Mg, K, P, Mn, Fe, Zn, Cu, B, S, Mo) in all tissue samples began with an initial digestion in concentrated nitric acid at 90 °C followed by three small additions of 30% hydrogen peroxide with a total time for digestion being ≈ 1 h. Digested samples were filtered and analyzed by inductively coupled plasma–optical emission spectroscopy (Perkin Elmer 4300 DV spectrometer) for those elements shown. There was insufficient tissue to measure shoot N concentrations of *Petunia* ‘Suncatcher Yellow’ cuttings fertilized with 0 or 3 g·L⁻¹.

For each species, the experiment employed a completely randomized design with fertilizer (six levels) as treatments. There were two propagation strips (replications) with seven individual cuttings (samples) per species per treatment. Cuttings were randomly assigned to fertilizer treatments. Analyses of variance and mean separation by Tukey’s honestly significant difference test at $P \leq 0.05$ were performed using SPSS 17.0 (IBM Corp., Armonk, NY).

Expt. 2. On 28 Feb. 2012, cuttings of *Impatiens hawkeri* ‘Celebrette Apricot’ and ‘Celebrette Rose Hot’, *Petunia* $\times$ hybrida ‘Suncatcher Yellow’, and *Pelargonium* $\times$ hortorum ‘Savannah Red’ were stuck and grown as described in Expt. 1. Data collection, calculation, and statistical analysis were performed as described in Expt. 1, except there were three propagation strips per species per treatment.

Results

Growth and morphology. The impact of fertilizer type on stem length and caliper compared with unfertilized cuttings was different among taxa (Figs. 1A–F and 2A–D). For example, 24 g·L⁻¹ CRF increased stem length of *Impatiens* ‘Celebrette Apricot’ and *Petunia* ‘Suncatcher Yellow’ by 25% (1.0 cm) and 98% (4.2 cm), respectively, compared with unfertilized cuttings. Alternatively, *Angelonia* ‘Sundancer Pink’ cuttings receiving WSF were 13% (1.2 cm) shorter than those receiving 24 g·L⁻¹ CRF. Stem length of *Nemesia* ‘Bluebird’ and *Pelargonium* was unaffected by fertilizers. Fertilizer did not affect stem caliper growth for two-thirds of the species in this study. However, stem caliper of *Nemesia* ‘Raspberry Sachet’ and *Petunia* ‘Cascadia Marshmallow Pink’ increased by up to 30% (0.5 mm) and 117% (1.6 mm), respectively, in response to CRF, whereas WSF increased stem caliper of *Impatiens* ‘Celebrette Apricot’ by 33% (1.1 mm) compared with unfertilized cuttings.

The effect of fertilization on SDM and RDM of cuttings varied among taxa (Figs. 1G–O and 2E–J). As CRF increased from 0 to 12 or 24 g·L⁻¹, SDM increased by 29% (54 mg; *Angelonia* ‘Sundancer Pink’) to 121% (125 mg; *Nemesia* ‘Raspberry Sachet’), whereas WSF increased SDM by 39% (47 mg; *Nemesia* ‘Bluebird’) to 150% (70 mg; *Petunia* ‘Suncatcher Yellow’) compared with unfertilized cuttings. The SDM of *Angelonia*

‘AngelFace White’ and *Pelargonium* was unaffected by fertilizers. The RDM of both *Angelonia* and *Nemesia* cultivars receiving WSF decreased by 30% (21 mg; *Angelonia* ‘Sundancer Pink’) to 41% (19 mg; *Nemesia* ‘Raspberry Sachet’) compared with unfertilized cuttings. Similarly, RDM for *Angelonia* ‘Sundancer Yellow’ and *Nemesia* ‘Bluebird’ and ‘Raspberry Sachet’ decreased by 35% (24 mg), 46% (18 mg), and 45% (21 mg),

Fig. 2. (A–J) Stem length, stem caliper, shoot and root dry mass, and root:shoot dry mass ratio of *Impatiens hawkeri* ‘Celebrette Apricot’ and ‘Celebrette Rose Hot’, *Pelargonium* $\times$ hortorum ‘Savannah Red’, and *Petunia* $\times$ hybrida ‘Suncatcher Yellow’ 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of 21 cuttings, and error bars represent SEM of the mean. Different letters are significantly different by Tukey’s honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

Fig. 3. (A–R) Tissue nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S) concentrations (%) of *Angelonia* 'AngelFace White' and 'Sundancer Pink' angelonia, *Nemesia* 'Bluebird' and 'Raspberry Sachet', and *Petunia* 'Cascadia Marshmallow pink' shoot tissue 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of two 14-cell propagation strips, and error bars represent SEM of the mean. Different letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

respectively, as CRF increased from 0 to 24 $\text{g}\cdot\text{L}^{-1}$. Alternatively, RDM of both *Impatiens* and *Petunia* cultivars and *Pelargonium* were not significantly affected by fertilizer. Although

the root:shoot (R:S) ratio of *Impatiens* 'Celebrette Apricot' and *Pelargonium* was unaffected or minimally affected by fertilizers, the R:S ratio of the other cultivars

was reduced by 48% (0.18, *Angelonia* 'Sundancer Pink') to 76% (0.34, *Nemesia* 'Raspberry Sachet') for cuttings receiving CRF or WSF.

Mineral nutrient concentrations. Both CRF and WSF increased nearly every primary macronutrient tissue concentration for each species (Figs. 3H–I and 4A–F). For example, cuttings propagated in substrate containing 24 g·L⁻¹ CRF had 52% (1.17%; *Angelonia* ‘Sundancer Pink’) to 103% (2.3%; *Nemesia* ‘Bluebird’) greater N, 42% (0.14%; *Impatiens* ‘Celebrette Rose Hot’) to 173% (0.35%; *Nemesia* ‘Bluebird’) greater P, or 50% (1.16%; *Angelonia* ‘AngelFace White’) to 124% (1.57%; *Pelargonium*) K, respectively, compared with unfertilized cuttings. Similarly, WSF increased N by 67% (1.5%; *Angelonia* ‘Sundancer Pink’) to 111% (2.44%; *Impatiens* ‘Celebrette Rose Hot’), P by 97% (0.30%; *Pelargonium*) to 315% (0.63%; *Nemesia* ‘Bluebird’), and K by 54% (1.8%; *Petunia* ‘Cascadia Marshmallow Pink’) to 132% (1.67%; *Pelargonium*) compared with unfertilized cuttings. The P concentration of *Petunia* ‘Suncatcher Yellow’ tissue was not significantly affected by fertilizers.

Fertilization affected secondary macronutrient tissue concentrations of species differently (Fig. 3J–R and 4G–L). Compared with unfertilized cuttings, tissue Ca increased by 28% (0.27%) for *Pelargonium* cuttings fertilized with WSF only, whereas 12 or 24 g·L⁻¹ CRF treatments had lower Ca by 27% (0.27% to 0.28%) for *Nemesia* ‘Bluebird’. Fertilizers had no significant effect on tissue Ca of the remaining species. Although tissue Mg for *Pelargonium* decreased by 17% to 21% (0.07% to 0.09%) or 32% (0.13%) for cuttings fertilized with 12 to 24 g·L⁻¹ CRF or WSF, respectively, compared with unfertilized cuttings, Mg concentrations decreased by 36% (0.24%) and 25% (0.23%) for *Nemesia* ‘Bluebird’ and ‘Raspberry Sorbet’ fertilized with 24 g·L⁻¹ CRF, respectively, and by 18% (0.16%) for *Impatiens* ‘Celebrette Rose Hot’ receiving WSF. Tissue Mg for the remaining species was unaffected by fertilizers. As CRF increased from 0 to 6 g·L⁻¹ or greater, tissue sulfur (S) of *Pelargonium* and *Petunia* ‘Cascadia Marshmallow Pink’ increased by up to 40% (0.14%) and 23% (0.14%), respectively. Alternatively, fertilizing *Impatiens* ‘Celebrette Rose’ and *Petunia* ‘Suncatcher Yellow’ cuttings with WSF reduced tissue S by 35% (0.30%) and 38% (0.38%), respectively. Fertilizers did not affect tissue S of the remaining species. The irrigation water used in these experiments, both with and without fertilizer, was acidified with sulfuric acid to reduce alkalinity and pH, likely providing cuttings with S.

Fertilizing cuttings of *Petunia* ‘Suncatcher Yellow’, *Angelonia* ‘Sundancer Pink’, and *Nemesia* ‘Bluebird’ with 3, 12, or 24 g·L⁻¹ CRF, respectively, increased tissue B concentrations by 61% (40.4 ppm), 60% (23.6 ppm), or 83% (35.6 ppm), respectively, compared with unfertilized cuttings. Similarly, WSF increased tissue B concentrations of both *Angelonia* cultivars, *Impatiens* ‘Celebrette Apricot’, and *Pelargonium* by 34% (22.3 ppm, *Impatiens* ‘Rose Apricot’) to 55% (21.5 ppm, *Angelonia* ‘Sundancer Pink’). Tissue B of *Impatiens* ‘Celebrette Rose

Fig. 4. (A–L) Tissue nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S) concentration (%) of *Impatiens hawkeri* ‘Celebrette Apricot’ and ‘Celebrette Rose Hot’, *Pelargonium xhortorum* ‘Savannah Red’, and *Petunia xhybrida* ‘Suncatcher Yellow’ shoot tissue 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of three 14-cell propagation strips, and error bars represent SEM of the mean. Different letters are significantly different by Tukey’s honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

Fig. 5. Tissue boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) concentrations of *Angelonia* 'AngelFace White' and 'Sundancer Pink' angelonia, *Nemesia* 'Bluebird' and 'Raspberry Sachet', and *Petunia* 'Cascadia Marshmallow pink' shoot tissue 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of two 14-cell propagation strips, and error bars represent ses of the mean. Different letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

Hot', *Nemesia* 'Raspberry Sachet', and *Petunia* 'Cascadia Marshmallow Pink' was unaffected by fertilizers. Although WSF did not affect tissue Cu concentrations of both *Angelonia* cultivars and *Petunia* 'Suncatcher Yellow', Cu levels in other taxa fertilized with WSF were 40% (29.8 ppm, *Nemesia* 'Bluebird') to 64% (156.6 ppm, *Impatiens* 'Celebrette Apricot') lower compared with unfertilized cuttings; CRF had minimal impact on Cu concentrations. Although fertilizers had little effect on tissue Fe for most species, increasing CRF from 0 to 24 g·L⁻¹

led to reduced Fe of *Nemesia* 'Raspberry Sachet' by 25% (72.2 ppm). Similarly, although CRF minimally affected tissue Mn of most species, WSF elevated Mn by 42% (49.7 ppm, *Impatiens* 'Celebrette Rose Hot') to 97% (55.3 ppm, *Angelonia* 'Sundancer Pink') compared with unfertilized cuttings. Although tissue Zn for *Petunia* 'Suncatcher Yellow' was unaffected by fertilizers, WSF increased Zn by 37% (30.2 ppm; *Impatiens* 'Celebrette Rose Hot') to 159% (75.8 ppm, *Nemesia* 'Bluebird') compared with unfertilized cuttings. Fertilizers had no effect on Mo

for each species (data not shown). Although not quantified, the use of tap water in our study may have contributed some mineral nutrients to the mist solution and, therefore, to plant tissue concentrations.

Discussion

We have only found one report on the use of CRFs during vegetative propagation of herbaceous perennial ornamental plants (Rowe and Cregg, 2002). However, to evaluate the effectiveness of using CRFs in propagation of

Fig. 6. Tissue boron (B), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) concentrations of *Impatiens hawkeri* 'Celebrette Apricot' and 'Celebrette Rose Hot', *Pelargonium xhortorum* 'Savannah Red', and *Petunia xhybrida* 'Suncatcher Yellow' shoot tissue 28 d after inserting cuttings into substrate containing 0, 3, 6, 12, or 24 g controlled-release fertilizer (CRF) per liter or provided water-soluble fertilizer (WSF) during propagation. Each symbol represents the mean of three 14-cell propagation strips, and error bars represent SEM of the mean. Different letters are significantly different by Tukey's honestly significant difference (HSD) test at $P \leq 0.05$ within each cultivar.

annual bedding plant species, we need to evaluate the impact on growth, morphology, and tissue nutrient levels. Shoot growth, including stem length and caliper and SDM, was generally enhanced with the application of CRF or WSF. Although we have found no data on the response of stem caliper or length of cuttings to fertilization during propagation, previous studies have reported an increase in SDM and stem length with fertilization (Rowe and Cregg, 2002; Santos et al., 2011b). Rowe

and Cregg (2002) reported that SDM of *Artemisia ludoviciana* 'Valerie Finnis', *Gaura lindheimeri* 'Whirling Butterflies', and *Nepeta faassenii* 'Six Hills Giant' increased, although varying in magnitude, as N from CRF increased from 0 to 2.13 g·L⁻¹. Similarly, Santos et al. (2011b) reported that SDM of *Petunia* 'Supertunia Royal Velvet' receiving macro-nutrients increased compared with cuttings receiving only micronutrients as the period of macronutrient application increased from

7 to 21 d. Producers could inhibit any excessive stem length resulting from CRFs by applying plant growth retardants or by shearing cuttings. Shearing may yield additional benefits such as increasing the R:S ratio and/or the sturdiness of rooted cuttings as measured by the sturdiness quotient (stem caliper/stem length; Currey et al., 2012).

A primary goal during cutting propagation is to produce fully rooted ("pullable") cuttings (Lopez and Runkle, 2008). Therefore, our data on the impact of CRF and WSF fertilization on RDM of cuttings is of special interest with reference to efficient propagation of cuttings. For several species, RDM decreased with CRF or WSF application. However, data from other studies demonstrate variation in the response of herbaceous cuttings impact of CRF or WSF during propagation on RDM. Rowe and Cregg (2002) reported that although increasing N from CRF from 0 to 2.13 g·L⁻¹ increased RDM of *Gaura*, RDM of *Artemisia* and *Nepeta* was unaffected by CRF. Alternatively, Santos et al. (2011b) reported that, compared with cuttings receiving only micronutrients, RDM of *Petunia* cuttings decreased as the number of days cuttings received mist containing macronutrients from WSF increased from 7 to 21 d. However, in another study, Santos et al. (2009) reported that RDM of *Petunia* 'Supertunia Royal Velvet' and 'Supertunia Priscilla' increased by 1021% and 143%, respectively, when clear water supplemented with WSF was applied to the basal end of cuttings during propagation.

Although RDM decreased with fertilization, all cuttings were fully rooted and considered "pullable" at the end of the 4-week propagation period (data not shown). Furthermore, Lopez and Runkle (2008) reported that *Petunia* 'Tiny Tunia Violet Ice' and *Impatiens* 'Harmony White' cuttings were considered fully rooted when RDM was 10 mg or greater and 30 mg, respectively. In our study, RDM of both *Impatiens* and *Petunia* cultivars cuttings exceeded the value for Lopez and Runkle (2008) reported for as necessary for fully rooted *Impatiens* and *Petunia* cuttings propagated in cells with a similar individual cell volume. Alternatively, we did not find other published guidelines for RDM for fully rooted cuttings of other taxa. However, we feel that when our observations on the pullability of rooted cuttings across taxa and fertilizer treatments in this study are taken together, the impact of CRF treatments on RDM does not preclude their use during cutting propagation.

Replenishing macro- and micronutrients tissue concentrations is another goal of fertilization during propagation. On arrival and receipt in the United States, cuttings originating from off-shore stock plant facilities generally have adequate tissue concentrations of mineral nutrient concentrations within recommended ranges (Santos et al., 2011a). However, although uptake and tissue content of nutrients including N, P, and K may increase throughout propagation, tissue nutrient concentrations of fertilized cuttings decline (Blazich, 1988; Santos et al., 2009, 2011b;

Svenson and Davies, 1995). Nutrient concentrations of shoot tissue were compared with species-specific published recommended sufficiency ranges for mineral nutrient concentrations to better evaluate the suitability of CRF for use in propagation (Gibson et al., 2007; Mills and Jones, 1996). Although there were some exceptions, cuttings propagated in substrates containing 6 g·L⁻¹ generally had tissue concentrations within the sufficiency ranges for established plants in the finishing phase of production.

When growth and morphology data (Figs. 1 and 2) are taken together with tissue nutrient concentrations (Figs. 3 to 6), it is difficult to justify the use of CRF above 6 g·L⁻¹. The use of 12 or 24 g·L⁻¹ CRF may be useful if producers aim for a “nutrient loading” effect for subsequent growth after transplanting. However, there were few statistical differences in growth, morphology, or nutrient concentrations for cuttings propagated in 12 or 24 g·L⁻¹ CRF compared with cuttings propagated in 6 g·L⁻¹. Furthermore, regression analyses suggest that increasing CRF above the rates used in this study would not further enhance tissue N levels. When the short duration of propagation is taken together with the decline in tissue nutrient concentrations and initial absence and subsequent development of roots, maintaining and/or restoring tissue nutrient concentrations to published sufficient ranges may be difficult to achieve. Alternatively, these ranges may not be appropriate for this crop stage, i.e., recently rooted cuttings. Because cuttings fertilized with greater amounts of CRF generally had statistically similar tissue concentrations as those fertilized with WSF, 6 g·L⁻¹ CRF appears to be a viable alternative for use in cutting propagation for a number of species.

Producers must consider several additional factors when evaluating CRFs for use in propagation. First, although our results suggest incorporating up to 24 g of CRF/L of substrate, the volume of substrate required per unit area for propagation trays is much

less than the amount of substrate required to for an equivalent area of flats, containers, or hanging baskets. Furthermore, although incorporating large amounts of CRF into substrate may initially induce “sticker shock,” the cost of providing CRF during propagation must be considered relative to the value of the tray of rooted cuttings. Using an average wholesale price for the cost of the CRF used in our experiment, it would cost ≈\$0.30 per tray of cuttings to provide 24 g·L⁻¹, a tray of rooted cuttings may cost from \$65 to \$75 (A. Pyle, personal communication). Additionally, CRF may add value for producers who must hold rooted cuttings, if planting is delayed, or as an additional source of nutrients during finishing.

Conclusions

CRFs generally increased tissue levels of macronutrients for most species in this study and, at the highest rates, were comparable to cuttings receiving WSF with respect to growth and morphology and tissue nutrient concentration. Specifically, incorporating 6 to 12 g·L⁻¹ CRF results in shoot tissue nutrient concentrations similar to cuttings propagated using WSF, yet minimizes some of the excessive growth associated with the highest rate of CRF. More research identifying the effect of substrate temperature and prill size and release pattern would assist in developing best management practices for the use of CRF in cutting propagation of herbaceous taxa.

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