Growth, Quality, and Economic Value Responses of Bedding Plants to Reduced Water Usage

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Abstract. This study analyzed the effects of two ranges of drying down of substrate moisture content (SMC) before re-watering on plant growth and development, postproduction quality, and economic value of bedding plants grown in 1.67-L containers during greenhouse production. The two SMC treatments were wide-range (WR) SMC (WR-SMC) for dry-down from container capacity (CC) of 54% SMC dried down to 20% SMC or narrow-range (NR) SMC (NR-SMC) for dry-down from CC of 54% SMC dried down to 40% SMC. Six bedding plant cultivars were used [Solenostemon scutellarioides ‘French Quarter’ (coleus); Petunia ×hybrida ‘Colorworks Pink Radiance’ (petunia); Lantana camara ‘Lucky Flame’ (lantana); Impatiens ×hybrida ‘Sunnpatiens Compact Hot Coral’ (SCC); ‘Sunnpatiens Spreading Lavender’ (SSL) (impatiens); and Salvia splendens ‘Red Hot Sally II’ (salvia)]. Shoot dry weight was reduced with WR-SMC on petunia, lantana, impatiens SCC, and salvia at the end of production. With WR-SMC, the petunia, SCC and SSL root ball coverage percentages were greater on the bottom of the container, whereas those of impatiens SSL and salvia were reduced. The WR-SMC increased petunia postproduction quality by increasing the flower number. Lantana and impatiens SCC inflorescence/flower and/or bud number were reduced with WR-SMC. The impatiens SSL flower number was unaffected by SMC treatment. Salvia grown with WR-SMC had increased postproduction quality. WR-SMC reduced postproduction water potential in petunia, lantana, and coleus, suggesting that plants with WR-SMC during production were acclimated to reduced irrigation administered during postproduction. WR-SMC saved labor due to less frequent watering and overhead-associated costs due to reduced bench space, with the exception of coleus and impatiens SSL, which used the same bench space as NR-SMC. Considering production and/or postproduction quality, using WR-SMC during greenhouse production is beneficial as an irrigation method for coleus, petunia, impatiens SSL, and salvia, but not for impatiens SCC or lantana grown in 1.67-L containers.

The wholesale value of bedding and garden plants was $1.86 billion in 2015, which was 44% of the total wholesale value of floriculture crops in the United States, thus making bedding and garden plants the largest crop segment in this industry. Annual bedding plants generated $1.3 billion, representing 69% of the total bedding and garden plant division. Although the wholesale value of bedding and garden plants had decreased 1% from the previous year, those sold in hanging baskets and containers 5 inches or larger increased, and those sold in smaller containers or flats were reduced compared with the previous year (USDA, 2016).

Considering the economic value of potted bedding plants and the economic and environmental needs to reduce irrigation water usage, many studies have been conducted to determine bedding plants’ responses to water deficits using one of two methods: holding the substrate moisture content (SMC) at a constant level or repeatedly drying down from container capacity (CC) to a lower SMC level. Lowering SMC to a constant 20% from 40% combined with lower fertilization increased flowering of petunia ‘Dreams White’, which increased the visual quality while lowering production costs (Alem et al., 2015). Conversely, it was reported that petunia ‘Hurrah White’ grown at a constant 10% SMC and impatiens (Impatiens walleriana ‘Cajun Violet’) grown at 30% SMC using the dry-down method reduced flower number (Blanusa et al., 2009; Chylifiski et al., 2007). Decreased irrigation water usage during greenhouse production increased water use efficiency in American alumroot (Heuchera americana), gaura (Gaura linheimeri), impatiens (Impatiens walleriana), salvia (Salvia splendens), and vinca (Catharanthus roseus) (Burnett and van Iersel, 2008; Garland et al., 2012; Jaleel et al., 2008; Nemali and van Iersel, 2008).

A greenhouse production challenge to growing bedding plants in smaller containers and flats is height control, which typically has been managed by withholding irrigation combined with several plant growth regulator applications to produce compact plants with shorter internodes (Dole and Wilkins, 1999). Reduced irrigation inhibited petunia (Petunia ×hybrid) shoot growth, which implied that lower SMC could be used as an effective growth control method during greenhouse production of petunias (Blanusa et al., 2009; Niu et al., 2006). Water deficits induced by amending the substrate with osmotic compounds produced more compact salvia (Salvia splendens ‘Bonfire’) with greater leaf area/height (Burnett et al., 2005).

Sensor-based irrigation systems are being used to reduce irrigation water usage and produce more compact plants with lower costs while increasing or maintaining their aesthetic quality. The sensor-based irrigation system was first developed by Nemali and van Iersel in 2006 to reduce water consumption by maintaining a distinct and constant SMC (Nemali and van Iersel, 2006). Previous research showed 40% SMC to be similar to the traditional well-irrigated treatment commonly used by growers for potted plant production, whereas 20% SMC was an alternative irrigation treatment that reduced water usage without detrimental effects on plant quality (Alem et al., 2015; Bayer et al., 2015; Guo et al., 2018; Jacobson et al., 2015).

Using a sensor-controlled dry-down method, the responses of two bedding plant species to wide-range (WR) SMC (CC dried down to 20% SMC) varied compared with narrow-range (NR) SMC (CC dried down to 40% SMC). WR-SMC produced more compact angelonia (Angelonia angustifolia ‘Angelface Blue’), but it did not impact heliotrope (Heliotropium arborescens ‘Simply Scentsational’) shoot growth; however, both species had more root growth with WR-SMC. WR-SMC increased the visual quality of both angelonia and heliotrope postproduction by increasing the percentage of plant shoots covered with inflorescences and decreased water input during production, thereby decreasing production costs (Guo et al., 2018).

Even though studies have been performed to determine plant responses to water deficits during greenhouse production, the effects of water deficits on postproduction quality remain unclear (Islam and Joyce, 2015). The objective of this study was to ascertain the effects of NR-SMC compared to WR-SMC irrigation methods on growth, development, and physiological parameters during the production of coleus, petunia, lantana, and salvia grown in 1.67-L containers. The new trend of growing bedding plant species in larger containers (USDA, 2016), much like potted flowering and foliage plants are produced, was further justification to study irrigation of bedding plants grown in pots rather than flats.
Table 1. Effect of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) on shoot dry weight (DW) and root ball coverage percentage on the bottom and side of Solenostemon scutellarioides 'French Quarter', Petunia × hybrida 'Colorworks Pink Radiance', Lantana camara 'Lucky Flame', and Impatiens × hybrida 'Sunpatiens Compact Hot Coral' (SCC) in 2017, and of 'Sunpatiens Spreading Lavender' (SSL) and Salvia splendens ‘Red Hot Sally II’ in 2018.

| SMC%   | Plant                  | Shoot DW | Root ball coverage (%) |
|--------|------------------------|----------|------------------------|
|        |                        | Bottom   | Side                   |
|        | WR-SMC Coleus          | 34.6 a   | 39.7 a                 |
|        | NR-SMC                 | 33 a     | 40.1 a                 |
| ANOVA  | NS                     | NS       | NS                     |
|        | WR-SMC Petunia         | 11.8 b   | 44.3 a                 |
|        | NR-SMC                 | 17.8 a   | 33.4 b                 |
| ANOVA  | **                     | *        | **                     |
|        | WR-SMC Lantana         | 8 b      | 30.5 a                 |
|        | NR-SMC                 | 12.6 a   | 32.3 a                 |
| ANOVA  | ***                    | NS       | NS                     |
|        | WR-SMC Impatiens SCC   | 7.1 b    | 21.4 a                 |
|        | NR-SMC                 | 8.5 a    | 13 b                   |
| ANOVA  | **                     | **       | NS                     |
|        | WR-SMC Impatiens SSL   | 12.5 a   | 63.5 b                 |
|        | NR-SMC                 | 13 a     | 81.1 a                 |
| ANOVA  | ***                    | *        | **                     |
|        | WR-SMC Salvia          | 11.7 b   | 56.9 b                 |
|        | NR-SMC                 | 16.6 a   | 75.5 a                 |
| ANOVA  | ***                    | **       | **                     |

*Means separated by Student’s t test at P ≤ 0.05.
NS, *, **, ***Nonsignificant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.

We used the same dry-down method as described previously (Guo et al., 2018) to apply SMC treatments, and we irrigated plants to CC (54%) after target SMC levels were indicated by sensor readings. The root substrate was allowed to dry down to the target SMC, and it was re-watered to CC repeatedly as needed. We determined whether plants produced with WR-SMC acclimated to infrequent irrigation during simulated shelf life and analyzed the economics of these irrigation methods by considering production inputs and shrinkage throughout the market channels. Finally, we quantified plant quality before and after simulated shelf life. Our hypothesis was that WR-SMC during production would lower irrigation-associated costs, control growth, better-acclimate plants to the postproduction environment, and allow plants to maintain higher visual quality during postproduction.

Materials and Methods

Plant material and growing conditions.
Rooted cuttings of coleus (Solenostemon scutellarioides) ‘French Quarter’, petunia (Petunia × hybrida) ‘Colorworks Pink Radiance’, lantana (Lantana camara) ‘Lucky Flame’, and impatiens (Impatiens × hybrida) ‘Sunpatiens Compact Hot Coral’ (SCC) grown in 102 liner trays were received and transplanted on 30 Jan. 2017. ‘Sunpatiens Spreading Lavender’ (SSL) grown in 102 liner trays and salvia (Salvia officinalis) ‘Red Hot Sally II’ seedlings grown in 128 plug trays with four seedlings per plug were received and transplanted on 15 Mar. 2018. All plants were purchased from Tagawa Greenhouses, Inc. (Denver, CO), and graded for uniformity on arrival. Each plant was transplanted to a 1.67-L (6.5-inch round) container (The HC Companies, Inc., Middlefield, OH) with commercial peat-based soilless root substrate (85% Canadian sphagnum peat moss and 15% perlite; BM 6; Berger, Saint-Modeste, Canada). During the greenhouse production period, a water-soluble fertilizer (20N–4.4P–16.6K; Peters 20–10–20; Scotts Miracle-Gro Company, Marysville, OH) root substrate drench after transplantation was allowed 14 d for root establishment before initiation of SMC treatments on 20 Feb. 2017 and 26 Mar. 2018. SMC treatments were continual throughout the production weeks. Electrical conductivity (EC) and pH readings were obtained weekly using the PourThru method (Wright, 1986) with Laqua Twin EC and pH meters (Spectrum Technologies Inc., Aurora, IL). No differences were found between SMC treatments for any of the cultivars.

Plants were grown in a glass wall and polycarbonate root greenhouse in College Station, TX, for two experiments from 30 Jan. to 5 May 2017 and from 15 Mar. to 18 May 2018. Environmental data were measured at the plant canopy level by WatchDog 450 data loggers and LightScout quantum light sensors (Spectrum Technologies Inc., Aurora, IL). The average temperatures and light intensities in the greenhouse during the experiment were 22.8 °C day/18.4 °C night in 2017 and 24.5 °C day/18.4 °C night in 2018. During production, the average daily light integral (DLI) and relative humidity were

![Fig. 1. Effects of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) according to the weekly growth index (GI).](image)
In 2017, plants were deemed marketable after 7 weeks of production (7 Apr.) for coleus, 8 weeks (14 Apr.) for petunia, and 9 weeks (21 Apr.) for lantana and impatiens SCC. At that time, plants were subjected to a simulated shipping process consisting of hand-watering to CC before moving plants under 50% shade cloth for 2 weeks for simulated shelf life; during that time, plants were only watered with reverse osmosis water when wilting began to occur. During postproduction, the average temperature, DLI, and relative humidity in the greenhouse were 22.3 °C day/19.5 °C night, 6.2 mol·m⁻²·d⁻¹, and 64.8% in 2017, and 21.7 °C day/20.0 °C night, 8.5 mol·m⁻²·d⁻¹, and 52.3% in 2018.

**SMC treatment.** One of two irrigation treatments, WR-SMC or NR-SMC, was applied during six experiments (one cultivar per experiment) during the production weeks. NR-SMC consisted of allowing the substrate to dry down to 40% SMC before hand-watering to CC (54% SMC), which was until the initiation of drainage. WR-SMC consisted of allowing substrate to dry down to 20% SMC before hand-watering to CC. SMC was defined as the percentage of Vw/VT (Vw is the volume of water and VT is the total volume of substrate particles, water, and air space). SMC was monitored by a watchdog 1000 series Micro Station and SM 100 WaterScout soil moisture sensors (Spectrum Technologies, Inc., Aurora, IL). There was one sensor per treatment per cultivar inserted in the root substrate of a container that was closer to the center of the greenhouse bench to reflect the average SMC of the treatment and to avoid the drying effect of the bend edges. Sensors recorded SMC every 30 min, and each irrigation event was determined based on the sensor readings (observed daily) and the calibration of the sensor.

**Sensor calibration.** Soil moisture sensors were calibrated by filling five 1-L plastic beakers with a 1-L volume of oven-dried root substrate. Substrate density was standardized by tapping dry substrate–filled plastic beakers five times from a uniform height of ≈3 to 6 cm above a sturdy table (Fonteno et al., 1995). Each beaker was emptied in one of five polyethylene plastic bags (Ziploc; S.C. Johnson & Son, Inc., Racine, WI), and 100, 200, 300, 400, or 500 mL of water was poured in one of the five bags. Root substrate was thoroughly mixed with the water and allowed to incubate for 24 h. All dry weight (DW), wet weight (WW), and the net weight of the beaker was measured and recorded. Root substrate was repacked into the same plastic beaker as previously described. Three sensor readings were performed at three different locations in the beaker to avoid performing readings too close to the edge of the beaker (according to the WaterScout SM 100 Soil Moisture Sensor Product Manual). SMC was calculated as SMC = (WW – DW) × 100% / 1000 (Cai et al., 2012).

**Fig. 2. Effects of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) on the stem caliper at the end of production of *Lantana camara* ‘Lucky Flame’ and *Impatiens* *sylvestris* ‘Suntan Compact Hot Coral’ (SCC) in 2017, and of *Salvia splendens* ‘Red Hot Sally II’ in 2018. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) × 100% / 1000.**

**Table 2. Effect of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) on bud, flower, and senesced flower number of *Petunia hybrida* ‘Colorworks Pink Radiance’ from production weeks 5 to 7 and 2 weeks postproduction in 2017.***

|                | Bud number | Flower number | Senesced flower number |
|----------------|------------|---------------|------------------------|
|                | Week 5     | Week 6        | Week 7                 | Week 1     | Week 2     |
| **WR-SMC**     | 19.4 **a** | 17.3 b        | 17.3 **b**             | 14.7 a     | 15.4 a     |
| **NR-SMC**     | 22.0 a     | 26.7 a        | 28.2 a                 | 7.5 b      | 10.6 b     |
| **ANOVA**      | NS         | ***           | ***                    | **         | **         |
| **Flower number** |           |               |                        |            |
| **WR-SMC**     | 18.3 b     | 21.0 b        | 29.8 b                 | 22.1 b     | 32.6 a     |
| **NR-SMC**     | 24.7 a     | 24.5 a        | 37.4 a                 | 33.0 a     | 23.4 b     |
| **ANOVA**      | **         | *             | *                      | **         | **         |
| **Senesced flower number** | |                    |                          | **         | **         |
| **WR-SMC**     | 1.9 a      | 13.2 a        | 26.1 a                 | 29.6 b     | 49.4 b     |
| **NR-SMC**     | 1.5 a      | 14.6 a        | 31.3 a                 | 52.8 a     | 89.9 a     |
| **ANOVA**      | NS         | NS            | NS                     | ***        | ***        |

*Means separation by student t test at P ≤ 0.05. NS, *, **, *** Nonsignificant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.*
Data collection. To perform an economic analysis of water usage, containers were weighed before each irrigation event during the production and postproduction stages of the experiments. After irrigation, containers were allowed to drain for 1 h and then reweighed. The weight difference was calculated and recorded to determine the total irrigation volume. Each irrigation event was documented and summed to determine the total number of irrigation events during production and/or postproduction.

Plant height and width were recorded weekly starting at production week 1 for all six different cultivars. Plant height was measured from the root substrate surface to the tallest point of the plant. Two plant widths were measured across the greatest plant width and the perpendicular width. The growth index (GI) was calculated as: GI = plant height/2 + (plant width1 + plant width2)/4 (Niu et al., 2007). At the end of production, the stem caliper was measured under the node of the third fully expanded leaf with a digital caliper on all six cultivars. The stem calipers on petunia, lantana, impatiens SCC, impatiens SSL, and salvia were collected at the end of postproduction. Leaf thickness between two major leaf veins was measured on a young, fully unfolded leaf with a digital caliper at the end of production and postproduction for all six cultivars. The bud, flower, and senesced flower number were measured weekly on petunia, lantana, and impatiens SCC. The same data were collected for impatiens SSL and salvia only at the end of production and postproduction. Leaf thickness between two major leaf veins was measured on a young, fully unfolded leaf with a digital caliper at the end of production and postproduction for all six cultivars. The bud, flower, and senesced flower number were measured weekly on petunia, lantana, and impatiens SCC. The same data were collected for impatiens SSL and salvia only at the end of production and postproduction.

Table 3. Effect of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) on bud and flower number of *Impatiens camara* 'Lucky Flame' and bud number of *Impatiens ×hybrida* 'Sunpatiens Compact Hot Coral' (SCC) during 2 weeks of postproduction in 2017.

|                                | WR-SMC | NR-SMC | ANOVA |
|--------------------------------|--------|--------|--------|
| Lantana bud number Wk 1        | 15.1 a | 7.3 b  | **     |
|                                |        |        |        |
| Lantana inflorescence number Wk 1 | 7.3 a | 6.7 b  | **     |
|                                |        |        |        |
| Impatiens SCC bud number Wk 1  | 38.2 b | 37.4 a | ***    |
|                                |        |        |        |
| *NS*, **, *** Nonsignificant or significant at *P* ≤ 0.05, 0.01, or 0.001, respectively. |

Means separation by Student's *t* test at *P* ≤ 0.05. *NS* Nonsignificant or significant at *P* ≤ 0.05, 0.01, or 0.001, respectively.

Fig. 3. Effects of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) on the leaf net photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (E) from production weeks 4 to 7 of *Lantana camara* 'Lucky Flame' and *Impatiens ×hybrida* 'Sunpatiens Compact Hot Coral' in 2017, and of *Impatiens ×hybrida* 'Sunpatiens Spreading Lavender' and *Salvia splendens* 'Red Hot Sally II' in 2018. Means were separated within the group by Student’s *t* test at *P* ≤ 0.05. Means with the same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) × 100% / 1000.
at the end of postproduction from the bottom of the root ball and both sides of the root ball. The root ball covering percentage was the percentage of the substrate surface covered by roots after removal from the container. The shoot coloring percentage and root ball coverage percentage were analyzed with Photoshop CS6 (Adobe Systems Inc., San Jose, CA). Photoshop quantified the colored area (flowers) and green area (leaves), and the total shoot area was calculated as the colored area plus the green area. The shoot coloring percentage was then calculated as the colored area divided by the total shoot area. To determine the root ball coverage percentage, Photoshop quantified the total root ball area as the root area plus the substrate area. The root ball coverage percentage was calculated as the root coverage area divided by the total area.

Experimental design and data analysis.
The experiment had a randomized complete design and involved two treatments (WR-SMC and NR-SMC) with 15 replications in 2017 and 10 replications in 2018. Each cultivar was analyzed separately. A one-way analysis of variance (ANOVA) procedure was used to test the effects of SMC treatments on plant growth. Data were analyzed by JMP (SAS Institute, Cary, NC). Mean separation was conducted using Student t tests if the significance level was 5%.

Results and Discussion

Plant morphology.
Coleus and impatiens SSL GI (data not shown; coleus: 32.4 cm, SD = 6.6 cm; impatiens SSL: 31.6 cm, SD = 0.9 cm) and shoot DW were unaffected by SMC treatment (Table 1). The GI of petunia and salvia were greater with NR-SMC 1 or 2 cm) and shoot DW were unaffected by SMC treatments at the bottom of the container, but not at the sides of the container (Table 1). Impatiens SSL and salvia had higher root ball coverage at the bottom and sides of the container with NR-SMC (Table 1). WR-SMC reduced the stem caliper of lantana, impatiens SCC, and salvia (Fig. 2).

The level of adaptation was highly dependent on species and cultivar drought tolerance. Impatiens SCC is a hybrid, drought-tolerant, compact plant with a root system adapted to full sun or part shade (Dole and Wilkins, 1999; Sakata Seed America, 2017; Sato and Minemura, 2014). This could explain why impatiens SCC with WR-SMC produced more roots without affecting shoot GI. In contrast to impatiens SCC, impatiens SSL was bred to have a spreading habit (Sato and Minemura, 2016). In our present study, impatiens SSL shoot DW, GI, and stem caliper were unaffected by SMC treatments, and only root growth was inhibited with WR-SMC. This indicated that by repeatedly drying down to 20% SMC, impatiens SSL redirected more energy to support shoot growth and flowering than root development. Coleus has a high water-use requirement and was irrigated more than the other cultivars. This trait minimized the difference between irrigation amount and frequency between WR-SMC and NR-SMC (Table 6) compared with the other cultivars tested; therefore, coleus morphological variables were unaffected.

A water deficit during production has been shown to cause shoot growth inhibition, including reduced leaf surface area, plant height, and shoot DW. Previous studies reported that petunia, salvia, and lantana shoot DW decreased as the SMC level decreased (Alem et al., 2015; Eakes et al., 1991; Kim and van Iersel, 2009). Lower SMC inhibited the shoot growth of other bedding plant species, including vinca, carnation (Dianthus caryophyllus), angelonia, American alumroot, and gaura (Alem et al., 2015; Burnett and van Iersel, 2008; Garland et al., 2012; Guo et al., 2018; Jacobson et al., 2015; Jaleel et al., 2008; Kim and van Iersel, 2009).

In an environment with a water deficit, root growth is favored over shoot growth (Taiz et al., 2015). This was considered beneficial for adaptation and surviving a water stress situation (Blum, 1996). Angelonia, heliotrope, carnation, crimson bottlebrush (Callistemon citrinus), geranium (Pelargonium shortorum), impatiens, and oleander (Nerium oleander) were reported to have a higher root density or root-to-shoot ratio with lower SMC (Álvarez et al., 2009, 2011, 2013; Alvarez and Sánchez-Blanco, 2013; Chylinski et al., 2007; Guo et al., 2018; Niu et al., 2008; Sánchez-Blanco et al., 2009).

Petunia grown in NR-SMC had higher flower and bud numbers 6 and 7 weeks after SMC treatments began. However, petunia grown in NR-SMC had higher senesced flower numbers; therefore, it had lower flower and bud numbers during postproduction (Table 2). Lantana and impatiens SCC bud, flower, and senesced flower numbers were unaffected by SMC treatments at the end of production (data not shown), with averages of 13.8 (SD = 1.4), 0.1 (SD = 0.1), and 0 for lantana and 46.6 (SD = 2.0), 5.8 (SD = 0.8), and 3.1 (SD = 0.5) for impatiens SCC, respectively. At the end of postproduction, lantana with NR-SMC had greater bud and inflorescence numbers because plants with NR-SMC produced more buds at the end of production (Table 3). During postproduction, the impatiens SCC bud number was greater with NR-SMC (Table 3), but the flower number was unaffected by SMC (data not shown), with averages of 4.1 (SD = 1.1) during the first week and 16.0 (SD = 1.8) during the second week. Impatiens SSL flower and bud numbers were not different based on SMC treatments during production and postproduction (data not shown), with averages of 5.3 (SD = 1.0) and 44.0 (SD = 2.3) for production and 18.2 (SD = 2.2) and 46.9 (SD = 4.1) for postproduction.

During flowering, plants are more susceptible to water stress. Research has indicated that, with a water deficit, root growth in deeper soil required allocation of photosynthetic products to root tips. However, during flowering, root growth is less pronounced.
Impatiens SSL
Impatiens SCC
or 0.01, respectively.

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NS, *, **, Nonsignificant or significant at

Different SMC was calculated as SMC = (substrate wet weight – substrate dry weight)

Fig. 5. Effects of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) on shoot coloring percentage at the end of production and the end of postproduction of Petunia 'Lucky Flame' in 2017, and of (d) salvia (Salvia splendens) 'Red Hot Sally II' in 2018 during production weeks and postproduction weeks. Means were separated by Student’s t test multiple comparisons at P ≤ 0.05. Means with the same letter are not different. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) × 100% /1000.

Table 4. Effect of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) on shoot coloring percentage for Petunia xhybrida ‘Colorworks Pink Radiance’, Lantana camara ‘Lucky Flame’, and Impatiens xhybrida ‘Sunpatiens Compact Hot Coral’ (SCC) in 2017, and of 'Sunpatiens Spreading Lavender' (SSL) in 2018.

Shoot color (%)  

|          | Production | Postproduction |
|----------|------------|----------------|
| Petunia  |
| WR-SMC   | 35.7 a     | 25.5 a         |
| NR-SMC   | 36.7 a     | 17.5 b         |
| ANOVA    | NS         | **             |
| Lantana  |
| WR-SMC   | 8.9 a      | 3.7 b          |
| NR-SMC   | 7.3 a      | 9.2 a          |
| ANOVA    | NS         | *              |
| Impatiens SCC |
| WR-SMC   | 5.8 b      | 31.4 b         |
| NR-SMC   | 17.1 a     | 44.3 a         |
| ANOVA    | **         | *              |
| Impatiens SSL |
| WR-SMC   | 11.3 a     | 19.8 a         |
| NR-SMC   | 11.2 a     | 25.2 a         |
| ANOVA    | NS         | NS             |

Means separation by student t test at P ≤ 0.05. NS, *, **, Nonsignificant or significant at P ≤ 0.05 or 0.01, respectively.

Fig. 6. Photographs of the effects of two substrate moisture contents (SMC): (1) wide-range SMC (WR-SMC; 54% to 20% SMC) and (2) narrow-range SMC (NR-SMC; 54% to 40% SMC) on shoot coloring percentage for Petunia xhybrida ‘Colorworks Pink Radiance’, Lantana camara ‘Lucky Flame’, Impatiens xhybrida ‘Sunpatiens Compact Hot Coral’, and Sunpatiens Spreading ‘Lavender’ at the end of postproduction in 2017 or 2018. SMC was calculated as SMC = (substrate wet weight – substrate dry weight) × 100% /1000.

Plants respond to water deficits by progressively closing the stomata to reduce evaporation water loss, thereby reducing Pn, gs, and E (Tezara et al., 1999). Studies have shown that the carnation, crimson bottlebrush, salvia, rose (Rosa spp.), and geranium leaf gas exchange rates decreased as the SMC level decreased (Álvarez et al., 2009, 2011; Álvarez and Sánchez-Blanco, 2013; Cai et al., 2012, 2014; Eakes et al., 1991; Sánchez-Blanco et al., 2009). In our study, lower photosynthesis rates with WR-SMC for lantana, impatiens SCC and SSL, and salvia led to reductions in their shoot and/or root growth. Even though other studies have shown that the petunia gas exchange rate decreased as the SMC level decreased, this discrepancy from our results could be due to the experimental methods or the lower SMC levels used in other studies (10% and/or lower SMC) (Kim et al., 2012; Nemali and van Iersel, 2008; Niu et al., 2006). With a water deficit, before the photosynthetic activity is affected, shoot inhibition can occur to redirect energy to support further root growth in some species (Boyer, 1970; Taiz et al., 2015). Our results for the leaf gas exchange rates indicated that WR-SMC inhibited petunia shoot growth without affecting its photosynthetic activity and stimulated petunia to have more root growth.

The leaf chlorophyll index quantified by the SPAD reading showed no difference between SMC treatments for the two impatiens cultivars (data not shown). Petunia and salvia with WR-SMC had higher SPAD readings, but lantana with WR-SMC had
lower SPAD reading at the end of production and postproduction (Fig. 4). SPAD is directly related to leaf thickness, nitrogen concentration, chlorophyll level, and water status (Basyouni et al., 2015; Martinez and Guiamet, 2004). In our study, the higher SPAD with NR-SMC for lantana could have been related to the higher leaf nitrogen concentration associated with higher-frequency watering and, therefore, fertilization with each irrigation event because no difference in leaf thickness was detected in any of the cultivars (data not shown). The higher SPAD reading for petunia and salvia with WR-SMC could have been due to lower leaf water content or increased leaf chlorophyll content (Martinez and Guiamet, 2004).

The water potential for coleus, petunia, lantana, and salvia was greater with NR-SMC during production. During postproduction, the water potential for coleus, petunia, and lantana was greater with WR-SMC, whereas that for salvia was unaffected by SMC (Fig. 5), indicating that WR-SMC during production increased water stress for all four species and reduced water stress during postproduction for coleus, petunia, and lantana. Midday water potential is commonly used as a reliable indicator of plant water stress severity (Jones, 2006; Kim et al., 2012; Shackel et al., 1997). During production weeks, plants with WR-SMC had a higher stress level. Similar results were reported for petunia, vinca, and rose (Kim et al., 2012; Kim and van Iersel, 2011). Our study was significant because WR-SMC during production decreased the water stress level of coleus, lantana, and petunia during postproduction, indicating a possible acclimation to water stress when plants are allowed to repeatedly dry down from CC to 20% SMC during production.

**Visual quality.** At the end of production, petunia, lantana, and impatiens SSL shoot coloring percentages were unaffected by SMC treatment; however, it was greater with NR-SMC for impatiens SCC (Table 4). At the end of postproduction, petunia with WR-SMC had a greater shoot coloring percentage, but lantana and impatiens SCC with NR-SMC had a greater shoot coloring percentage, and impatiens SSL shoot coloring percentage was unaffected (Table 4; Fig. 6).

Petunia with WR-SMC had a higher shoot coloring percentage during postproduction because of the increased flower number. Lantana with WR-SMC had a lower shoot coloring percentage due to the lower flower number during postproduction. Impatiens SCC with WR-SMC produced fewer buds; therefore, it had a lower shoot coloring percentage. Impatiens SSL flower number and bud number were unaffected by SMC treatment, as were their shoot coloring percentages.

At the end of production, salvia visual quality was not different between SMC treatments, except NR-SMC resulted in an increased vegetative stem segment with leaves

### Table 5. Effect of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) on total stem and postproduction of *Salvia splendens* ‘Red Hot Sally II’ in 2018.

|                      | Total stem ht (cm) | Vegeatative stem segment (cm) | Inflorescence segment (cm) | Inflorescence number | Chlorotic leaf number |
|----------------------|--------------------|--------------------------------|---------------------------|----------------------|-----------------------|
|                      | With leaves        | With leaves                     | With fresh flowers         | With fresh flowers   |                       |
|                      | End of production  | End of production               |                           |                      |                       |
| WR-SMC               | 38.9 b             | 25.4 b                          | 13.1 a                    | 4.8 a                | 0 a                   |
| NR-SMC               | 41.6 a             | 28.0 a                          | 13.6 a                    | 2.2 a                | 0 a                   |
| ANOVA                | **                | NS                             | **                        | NS                   | **                    |
| End of postproduction| WR-SMC             | 45.8 b                          | 23.9 a                    | 5.3 a                | 0.6 a                 |
|                      |                     |                                 |                           |                      |                       |
|                      | NR-SMC             | 49.3 a                          | 25.5 a                    | 0.7 b                | 1.2 a                 |
|                      |                     |                                 |                           |                      |                       |

Means separation by Student t-test at P ≤ 0.05.

**NS** Non-significant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.

### Table 6. Production irrigation and associated economic implications of *Solenostemon scutellarioideae* ‘French Quarter’, *Petunia ×hybrida* ‘Colorworks Pink Radiance’, *Lantana camara* ‘Lucky Flame’, and *Impatiens ×hybrida* ‘Sunpatiens Compact Hot Coral’ (SCC) in 2017; ‘Sunpatiens Spreading Lavender’ (SSL) and *Salvia splendens* ‘Red Hot Sally II’ in 2018, grown at one of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) during 8 weeks of greenhouse production.

|                      | Estimated pot number/bench | Space saved (%) | Total no. of irrigation events | Labor saved (%) | Irrigation amount (L/pot) | Irrigation amount saved (%) |
|----------------------|-----------------------------|----------------|-------------------------------|----------------|--------------------------|----------------------------|
|                      | WR-SMC                      | 41.0 b          | 7.8 b                         | 11 b           | 8.3 b                    | 5.6 b                      |
|                      | NR-SMC                      | 38.0            | 0.0                           | 12 a           | 0.0                      | 5.5 a                      |
| Petunia              | WR-SMC                      | 51.0            | 24.1                          | 8 b            | 27.3                     | 3.6 a                      |
|                      | NR-SMC                      | 39.0            | 0.0                           | 11 a           | 0.0                      | 3.9 a                      |
|                      | WR-SMC                      | 71.0            | 32.2                          | 8 b            | 11.1                     | 3.1 a                      |
|                      | NR-SMC                      | 48.0            | 0.0                           | 9 a            | 0.0                      | 3.5 a                      |
| Lantana              | WR-SMC                      | 81.0            | 6.8                           | 7 b            | 22.2                     | 2.9 b                      |
|                      | NR-SMC                      | 76.0            | 0.0                           | 9 a            | 0.0                      | 3.8 a                      |
|                      | WR-SMC                      | 67.0            | 0.0                           | 7 b            | 12.5                     | 3.8 a                      |
|                      | NR-SMC                      | 67.0            | 0.0                           | 8 a            | 0.0                      | 3.5 a                      |
|                      | WR-SMC                      | 78.0            | 13.4                          | 7 b            | 36.4                     | 3.9 b                      |
|                      | NR-SMC                      | 67.0            | 0.0                           | 11 a           | 0.0                      | 5.9 a                      |

Means separation by Student t-test at P ≤ 0.05.

**NS** Non-significant or significant at P ≤ 0.05, 0.01, or 0.001, respectively.
compared with that treated with WR-SMC, thereby increasing the total stem height. After 2 weeks of postproduction, salvia with NR-SMC had increased abscised leaves, abscised flowers, and numbers of senesced inflorescences and chlorotic leaves (Table 5).

Previous research showed that using less SMC produced Salvia splendens with higher visual quality and improved tolerance to low SMC compared with untreated plants (Eakes et al., 1991). Drought-induced leaf abscission was believed to contribute to plant survival under water deficit conditions by relocating nutrients to the rest of the plant and reducing water loss through leaf transpiration. Chlorophyll degradation led to leaf chlorosis as part of the process of drought-induced leaf abscission (Munné-Bosch and Alegre, 2004).

In our research, even though salvia water potential was not different between SMC treatments during postproduction, plants with NR-SMC had higher chlorotic leaf numbers and increased segments of vegetative stems with abscised leaves. This indicated that they had a more severe response to a water deficit during postproduction compared with plants with WR-SMC. When combined with lower inflorescence quality, this indicated that plants with NR-SMC declined faster during postproduction.

Irrigation and associated economic implications. In this study, we considered NR-SMC equivalent to the traditional, well-irrigated method that is currently used by floral industry growers for potted plant production. Compared with those treated with NR-SMC, lantana, impatiens SCC, petunia, and salvia treated with WR-SMC had a smaller canopy; therefore, they required less bench space, which may translate to lower overhead costs associated with bench space (because they are normally applied based on the number of square feet per week). Compared to those treated with NR-SMC, coleus, petunia, lantana, impatiens SCC, and salvia saved 7.8%, 24.1%, 32.2%, 6.8%, and 13.4% on bench space, respectively, during production (Table 6). Impatiens SSL canopy size was unaffected by SMC treatments; therefore, no overhead space was saved. During the production weeks, WR-SMC required fewer total irrigation events; therefore, coleus, petunia, lantana, impatiens SCC, and salvia saved 8.3%, 27.3%, 11.1%, 22.2%, 12.5%, and 36.4% on irrigation-related labor, respectively. Although coleus, petunia, lantana, and impatiens SSL grown in WR-SMC required fewer total irrigation events, the irrigation amount used was unaffected by SMC (Table 6).

During postproduction, petunia, lantana, impatiens SCC, and salvia grown in WR-SMC saved 15.5%, 33.7%, 8.8%, and 14.9% on bench space, respectively. Coleus with WR-SMC required more bench space than coleus with NR-SMC. Impatiens SSL bench space was the same regardless of the SMC treatment used. Only petunia saved 25% on irrigation-related labor when the total number of irrigation events for other cultivars was unaffected by the SMC treatment. For all six cultivars, the postproduction irrigation amount was unaffected by SMC (Table 7).

Table 7. Postproduction irrigation and associated economic implications of Solenostemon scutellarioides ‘French Quarter’, Petunia ×hybrida ‘Colorworks Pink Radiance’, Lantana camara ‘Lucky Flame’, and Impatiens ×hybrida ‘Sunpatiens Compact Hot Coral’ (SCC) in 2017; ‘Sunpatiens Spreading Lavender’ (SSL) and Salvia splendens ‘Red Hot Sally II’ in 2018, grown at one of two substrate moisture contents (SMC): (1) wide range (WR) (54% to 20% SMC); and, narrow range (NR) (54% to 40% SMC) during 2 weeks of simulated shelf life.

| Table 7   | Estimated pot number/bench | Space saved (%) | Total no. irrigation event | Labor saved (%) | Irrigation amount (L/pot) | Irrigation amount saved (%) |
|-----------|----------------------------|-----------------|---------------------------|----------------|--------------------------|----------------------------|
| Coleus    | WR-SMC                     | 29.0           | –12.2                     | 6              | a                        | 2.0                        | 10.5                       |
|           | NR-SMC                     | 32.0           | 0.0                       | 6              | a                        | 2.2                        | 0.0                        |
| Petunia   | WR-SMC                     | 31.0           | 15.5                      | 3              | b                        | 25.0                       | 1.3                        | 7.5                        |
|           | NR-SMC                     | 26.0           | 0.0                       | 4              | a                        | 0.0                        | 1.4                        | 0.0                        |
| Lantana   | WR-SMC                     | 63.0           | 33.7                      | 3              | a                        | 0.0                        | 1.1                        | 23.6                       |
|           | NR-SMC                     | 42.0           | 0.0                       | 3              | a                        | 0.0                        | 1.4                        | 0.0                        |
| Impatiens | SCC                       | WR-SMC         | 73.0                      | 8.8            | 3                        | a                          | 0.0                        | 1.4                        | –34.5                      |
|           | NR-SMC                     | 66.0           | 0.0                       | 3              | a                        | 0.0                        | 1.0                        | 0.0                        |
| Impatiens | SSL                       | WR-SMC         | 55.0                      | 0.1            | 4                        | a                          | 0.0                        | 1.7                        | 12.1                       |
|           | NR-SMC                     | 55.0           | 0.0                       | 4              | a                        | 0.0                        | 1.9                        | 0.0                        |
| Salvia    | WR-SMC                     | 71.0           | 14.9                      | 4              | a                        | 0.0                        | 2.1                        | 6.1                        |
|           | NR-SMC                     | 60.0           | 0.0                       | 4              | a                        | 0.0                        | 2.2                        | 0.0                        |

1Estimated container number/bench was calculated as standard bench size (19.5” × 5.5”)/average canopy size of the plant.

2Space saved was calculated based on the difference in final spacing between WR-SMC and NR-SMC.

3Total no. of irrigation events during 2 weeks of postproduction simulated shelf life.

4Means were separated by Student t-test at *P* < 0.05. Means with the same letter are not different.

5Labor saved was calculated based on the difference in the number of irrigation events between WR-SMC and NR-SMC.

6Total irrigation amount per container was the sum of each irrigation water input during 2 weeks of postproduction simulated shelf life.

7Irrigation amount saved was calculated based on the difference in the total irrigation amount between WR-SMC and NR-SMC.

Responses and acclimation to WR-SMC varied among cultivars. Petunia and impatiens SCC with WR-SMC had higher root ball coverage percentages, whereas impatiens SSL and salvia with WR-SMC had lower root ball coverage percentages. The WR-SMC reduced lantana and impatiens SCC postproduction quality by reducing flower numbers and/or bud numbers. Coleus and impatiens SSL morphology was unaffected by SMC. Coleus, petunia, and lantana showed that plants with WR-SMC had decreased water stress (less negative water potential) during postproduction, indicating that plants exposed to a mild water deficit during production were acclimated to water stress.

The WR-SMC reduced the total number of irrigation events for all four species tested,
but it did not affect the irrigation volume delivered to coleus, petunia, lanata, and impatiens SSL. However, WR-SMC saved labor during production for all six cultivars and reduced bench space, with the exception of coleus and impatiens SSL. Based on the partial budget modeling procedures we used in this experiment, WR-SMC proved to be a more cost-efficient production method for all six bedding plant cultivars grown in 1.67-L containers. However, considering the crop quality and flower number, WR-SMC is not recommended for lantana ‘Lucky Flame’ and impatiens SCC produced in a greenhouse. Our results suggest that using WR-SMC is the best-practice irrigation method for these cultivars of coleus, petunia, impatiens SSL, and salvia during greenhouse production.

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